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1971

COMPARATIVE ATTRACTION OF DOUGLAS-FIR BEETLES TO FRONTALIN AND TREE VOLATILES

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ACKNOWLEDGMENTS

We thank Dr. G. B. Pitman, Boyce Thompson Institute, Grass Valley, California; Dr. W. D. Bedard, Pacific Southwest Forest and Range Experiment Station, Berkeley, California; and Dr. J. O. Rodin, Stanford Research Institute, Menlo Park, California, for aiding us in our efforts to obtain frontalin and other materials and technical advice. Assistance in designing the study and statistical analyses of data was received from Mr. M. A. Marsden, and chromatographic analysis of monoterpenes was performed by Dr. R. J. Steinhoff--both of the Forestry Sciences Laboratory, Moscow, Idaho. Scolytids were identified for us by Dr. S. L. Wood, Brigham Young University, Provo, Utah. Mr. L. E. Merrifield, student in Entomology, University of Idaho, ably assisted with fieldwork and sexed most of the specimens. Dr. J. H. Borden, Simon Fraser University, Burnaby, B.C., reviewed the manuscript and provided us suggestions for its improvement.

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ABSTRACT

Attractiveness of frontalin and constituents of resin were compared to Douglas-fir sections infested with unmated female Douglas-fir beetles [*Dendroctonus pseudotsugae* Hopk. (Coleoptera: Scolytidae)]. Four times more beetles responded to log sections infested with female beetles than to the next best treatment, a combination of frontalin and resin. When frontalin was combined with either resin, or most of its monoterpenes, a synergistic effect occurred. Equal numbers of male and female Douglas-fir beetles were attracted to resin and monoterpenes; the addition of frontalin to them resulted in catches of 2 to 4 males per female. Three species of predators and 23 species of other bark beetles were caught, mostly in a study area containing felled trees. Numbers of predators and bark beetles did not differ significantly by treatment but sex ratios of some species favored females. Included among bark beetles caught was a new species of *Hylurgops*, females of which were attracted to a log section containing female Douglas-fir beetles. Applied to live trees, the attractive treatments may be sufficient to induce attacks by wild Douglas-fir beetles. Use of attractants on mechanical traps instead of trees would be enhanced by the additional attractants apparently present in infested logs.

Introduction

The Douglas-fir beetle [illegible] is one of several destructive bark beetles in the Western United States. It usually breeds in damaged trees, but periodically amasses great numbers and kills millions of board feet of mature Douglas-fir timber (Furniss and Orr 1970). Prevention of outbreaks might be achieved by either stand sanitation (destruction or removal of attractive host material such as windthrow) or logging of mature and overmature trees (Furniss 1959); but neither action is practical in the remote and extensive areas that are typical of the beetle's range. Trap trees (live trees felled to attract beetles) have been suggested for controlling the beetle, but their effectiveness has not been demonstrated. Such trees tend to be inefficient trappers of beetles because beetles usually attack felled trees in low density, and avoid the sun-lighted parts of the stem. Also, cutting of trap trees prior to beetle flight in the spring is difficult because of adverse weather and inaccessibility. Where recreation and watershed values are paramount, use of trap trees might be more destructive than beneficial. Insecticides are effective in killing broods in felled trees (Gibson 1957; Rudinsky, Terrier and Allen 1960) or preventing attacks (Furniss 1962), but these methods are uneconomical or undesirable to use in most instances.

Because of the great economic loss caused by the beetle and lack of a generally applicable means of regulating populations of beetles that cause it, we have turned our attention to development and use of chemical attractants produced by host trees and beetles. If determined to be effective, selective, and economical, these attractants would lend flexibility to the integrated courses of action available to resource managers in protecting susceptible Douglas-fir stands.

Attraction Literature

One of us (Furniss) demonstrated in 1959 that live Douglas-fir trees baited with fresh-cut slabs containing feeding female beetles were attacked by wild beetles (U.S. Forest Service 1960). McMullen and Atkins (1962) found that logs infested with female Douglas-fir beetles were more attractive than either uninfested logs or logs containing both female and male beetles. The theory has been advanced that monoterpenes of Douglas-fir resin serve as host attractants for the first (pioneer) beetle attack (Rudinsky 1966a). Also, it is known that pheromones secreted during the early stages of attack by female beetles greatly increase the attraction and result in aggregation and mass attack by additional beetles of both sexes. Such mass attack in a confined time period may be helpful to the beetles in overcoming resistance of live trees.

The monoterpenes of Douglas-fir wood resin include α-pinene, camphene, β-pinene, myrcene, 3-carene, and limonene (Hanover and Furniss 1966); α-pinene is by far the most abundant; however, camphene is present in minute amounts. Heikkenen and Hrutfiord (1965) reported that α-pinene attracts, but β-pinene repels, Douglas-fir beetles; and they hypothesized that proportions of these two monoterpenes in trees may determine which trees are attacked. Rudinsky (1966b) observed that solutions of ethyl alcohol and α-pinene, camphene, limonene, and raw resin attracted more Douglas-fir beetles than did an uninfested log; β-pinene and myrcene were relatively unattractive.

Pitman and Vité (1970) reported that frontalin (a pheromone found in several *Dendroctonus* species) and camphene are involved in the aggregating mechanism of the Douglas-fir beetle. Their discovery prompted us to compare the attractiveness of frontalin, six monoterpenes, resin, and log sections infested with unmated female beetles (♀ logs) simultaneously in replicated field tests. Such information was sought to aid us in selecting the most attractive materials for future assessment of their value in aggregating wild beetles for control or survey purposes. Comparison of synthetic attractants (frontalin and monoterpenes) with the natural attractant provided by the female infested logs would also indicate whether additional attractants were likely to occur in the latter. We also were interested in the attractiveness of these materials to predacious insects and other species of bark beetles that might be in flight in the experimental area. Results of these field tests are reported here.

Methods

Tests were conducted between May 21 and June 2, 1970, on various sites in Boise Basin Experimental Forest near Idaho City, Idaho (table 1).

Treatments tested are listed in table 2. Purity of 0.2 µl samples of undiluted monoterpenes was checked at our laboratory by gas liquid chromatography (GLC) equipped with an electronic integrator. The column used was 6' of B, B' Oxydipropionitrile 15: 100 WAW. Monoterpenes were identified by their retention times.

Table 1.--*Characteristics of trapping locations in Boise Basin Experimental Forest, Idaho, 1970*

Location	Elevation	Aspect	Topography	Forest type	Estimated beetle population	Source of beetles
	Feet					
1. Slaughterhouse Gulch	4,100	E	Open ravine	[1]PP/DF	Medium	Scattered 1969-attacked trees nearby.
2. Bannock Creek	4,100	E	Ravine & bench	PP/DF	Heavy	Incoming beetles attracted to felled trees.
3. Bannock Creek	4,600-4,700	E	Lower slope	DF/PP	Heavy	Among 12-15, 1969-attacked trees.
4. Bannock Creek	5,000-5,200	N	Ravine	DF/PP	Light	None evident.
5. Bannock Creek	5,200-5,400	N	Mid-slope	DF/PP	Light to medium	Scattered 1969-attacked trees.

[1]PP = Ponderosa pine; DF = Douglas-fir.

Table 2.--*The number and sex of Douglas-fir beetles caught and treatment used, Boise Basin experimental Forest, Idaho, 197*

Treatment[1]	May 21			May 22			May 24			May 25			May 26			June 2			Total		
	♀	♂	Σ	♀	♂	Σ	♀	♂	Σ	♀	♂	Σ	♀	♂	Σ	♀	♂	Σ	♀	♂	Σ
GROUP I[2]																					
1. Camphene										4		4	1	2	3	1	1	2	6	3	9
2. Limonene										2	3	5	1	2	3		1	1	3	6	9
3. α-pinene											1	1	1	3	4		1	1	1	5	6
4. β-pinene													4	2	6				4	2	6
5. Mixture B				1		1				3		3		1	1				4	1	5
6. Resin													2	2	3	1		1	2	2	4
7. Myrcene											2	2	1	1	2				1	3	4
8. Mixture A		3	3											1	1					4	4
9. 3-carene													2	1	3				2	1	3
10. Mixture C				1		1										1		1	2		2
TOTAL		3	3	2		2				9	6	15	11	15	27	3	3	6	25	27	52
GROUP II[3]																					
11. Frontalin + resin	6	8	14		5	5	6	16	22	1	3	4	22	38	7[a]	26	18	44	61	120	181 a
12. Frontalin + α-pinene		1	1							2		2	6	72	78	4	30	32	54	103	157 b
13. Frontalin + limonene							4	10	14	2	1	3		2	2	2	10	12	18	63	81 b
14. Frontalin + myrcene							1	1	2				4	7	11	2	5	7	9	13	22 b c
15. Frontalin + β-pinene								3	3				2	6	8	3	4	7	5	13	18 b c
16. Frontalin + Mix. B				1		1		1	1	3		3	2	4	6	1	3	4	6	9	15 b c
17. Frontalin + Mix. C								2	2					13	13		1	1		16	16 b c
18. Frontalin + Mix. A				2	2	4		3	3	2	1	3	1	1	2				5	7	12 b c
19. Frontalin + camphene													1	2	3		2	2	1	4	5 c
20. Frontalin + 3-carene							2		2		1	1		1	1				2	3	5 c
TOTAL	6	9	15	1	5	6	13	38	51	10	5	15	39	156	195	39	73	112	171	381	552
GROUP III																					
21. 50^{+}_{-} in log	6	4	10	30	125	155	1	2	3	102	12	114	11	1	12	13	2	15	163	146	309 d
22. Frontalin[4] + resin	1	7	8	8	34	42		1	1	1	2	3				22	13	35	32	179	211 e
23. Frontalin + α-pinene[4]				22	44	66	1	6	7		2	2	1	3	4	3		3	27	89	116 e f
24. Frontalin + Mix. D[5]	1	6	7	5	20	25	1	3	4	3	6	9		4	4	7	16	23	21	73	94 f
25. Frontalin + Mix. D[6]		1	1	1	6	10	1	3	4	3	6	9		4	4	7	16	23	20	76	96 f
26. Frontalin + camphene[7]				1	7	11								1	1	4	6	10	11	24	35 f
27. Frontalin[3]					1	1										1	3	4	1	16	23 g
28. α-pinene[4]				2	2	4				1	2	3					1	1	3	5	8 h
29. Camphene[2]				1	2	3													1	4	5 h
30. Check																					
TOTAL	8	18	26	70	244	314	3	16	19	150	33	183	112	172	284	80	60	140	322	743	1,065
GRAND TOTAL																			421	1,167	1,588

[1]A = α-pinene + camphene + limonene
B = β-pinene + myrcene + 3-carene
C = all 6 monoterpenes
D = α-pinene + camphene
[2]Supplier: Chemical Samples Co. (CS)
[3]Frontalin supplied by Boyce Thompson Institute, [illegible]
[4]Supplier: Stanford Research Institute.
[5]Totals having unlike, single, alphabetical [illegible] letter at the [illegible] Duncan's [illegible] test [illegible].

Log sections (fig. 1A) were infested with female beetles nightly for the first three replications, but later tests employed log sections infested up to 7 days previously. Monoterpenes and frontalin were kept refrigerated as much as possible prior to placement in the field. They were delivered by diffusion to the air by two methods: (1) 1.8-ml. capacity polyethylene plastic stoppers[1] (fig. 1B); and (2) inverted 1-oz. capacity glass jars, the lids of which were perforated; inside these jars, the $\frac{1}{2}$-dr. glass vials containing the candidate attractants were open and in an upright position (fig. 1C). Resin was collected from cut faces of a single live tree daily in 1-dr. open vials from which odors were dispersed. Approximate amounts of chemicals dispensed into plastic stoppers per replicate were: frontalin, 10 mg.; camphene, 50 mg.; and monoterpenes, 0.6 ml. total (divided equally when more than one monoterpene was added). Amounts dispensed into glass vials per replicate were: frontalin, 10 mg.; camphene, 50 mg.; α-pinene, 20 mg.; and resin, 0.1-0.2 ml.

Approximately 5 mg./hr. of frontalin is diffused from plastic stoppers under field conditions conducive to beetle flight (Dr. G. B. Pitman, personal communication). At 6,000 feet elevation and 73° F., 1 mg./hr. of frontalin, α-pinene, or camphene (a solid) is diffused from glass jar dispensers; at 88° F. the rate is increased to 2 mg./hr. (Dr. J. O. Rodin, personal communication). The number of female equivalents represented by these delivery rates is unknown. It has been suggested that mass aggregation of the western pine beetle, *Dendroctonus brevicomis* Lec., requires a concentration of frontalin 10 times that produced naturally by attacking beetles (Vité and Pitman 1970).

The attractant-containing delivery units (log sections, stoppers, and bottles) were attached to $\frac{1}{4}$-inch mesh wire screen traps to which Stickem Special had been applied with a paint roller (fig. 2). The cylindrical screen traps were 4 feet long and 15 inches in diameter and were mounted vertically on $\frac{7}{8}$-inch diameter, 6-foot-long water pipes driven into the ground. Rigidity was provided by a circular support of $\frac{3}{8}$-inch plywood inside, near the middle of the cage. Wire stays extended across the top of the support through the screen and at the bottom of the cage running from the screen to the pipe. Traps were placed at distances varying from approximately 75 to 150 feet apart; the intention was to avoid such closeness that intermingling of odors from adjacent traps might affect beetle response.

The plastic stoppers were held to cages by spring-type paper fasteners hung on wire hooks (fig. 1B). Jars, held to traps by wires, were covered with aluminum foil to reflect heat (fig. 1C). Stoppers and jars were fastened on the outside of cages for convenience and positioned in the shade of the plywood shelf to slow evaporation of attractants. Female logs in the traps were placed inside open paper bags to avoid frass contaminating the plywood shelves on which they rested (fig. 1A).

Each of the 30 treatments was applied daily for 6 days, a total of 180 trap days. Because it was physically impossible to fit all 30 traps 75-150 feet apart in some restricted test locations, we divided the traps and treatments into 3 groups of 10 each. Thus, it took 3 days to test each treatment once at a location. This formed 2 (3 by 3) Latin Squares for the effect of test location and test period. Within the study areas, treatments were assigned to traps at random. After 30 treatments had been applied, traps were moved to new locations, except for Location 2 where traps were left for 6 days.

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[1]Polyethylene closed bottom stoppers with polyethylene top inserts for 3-dr. vials, No. 10-5945. Ace Scientific Supply Co., Inc., 1420 E. Linden Ave., Linden, New Jersey 07036.

Figure 1.--Methods of [illegible] Douglas-fir beetle and associated insects (circles indicate trapped beetles): A, Stem section infested with 50 unmated female beetles (paper bag removed); B, hollow polyethylene plastic stopper; C, glass jar with perforated lid and vials inside (aluminum foil cover removed).

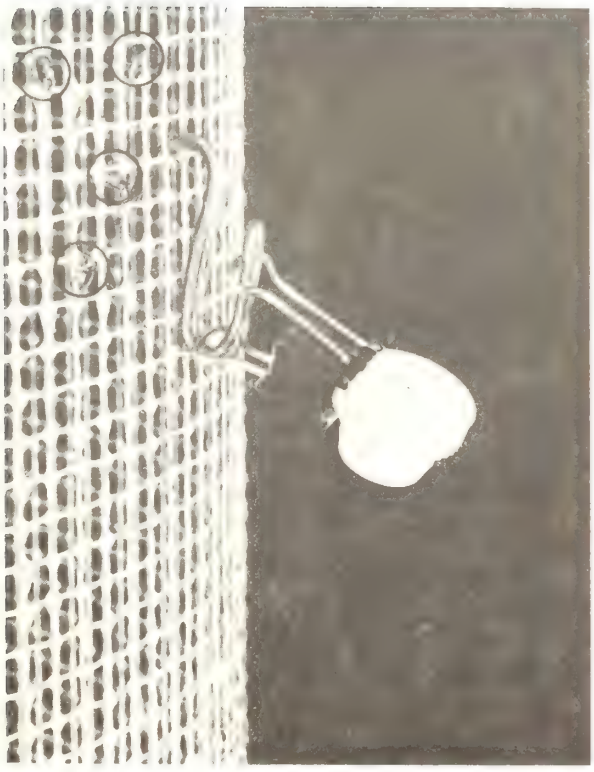

Figure 2.--Wire screen sticky trap used to catch beetles during tests of the attractiveness of derivatives of Douglas-fir resin, frontalin, and stem sections infested with female beetles.

Numbers of Douglas-fir beetles caught were subjected to analysis of variance using unweighted means (table 3). The criterion used in the analysis was the transformed counts of insects caught by species. Counts were transformed by the $\log_e$ of counts + 0.5 to stabilize variance due to zero counts. Other abundant species (predators and other bark beetles) were analyzed similarly, using Location 2 data only, due to scarcity of these species elsewhere.

Each day's catch of Douglas-fir beetles, predators (clerids, ostomids) and other bark beetles was removed during the following morning before additional insects began flying. To dissolve the Stickem Special, specimens were placed in labeled vials of Shell solvent. Later, specimens were removed, dried, and stored in alcohol for subsequent identification and sexing.

After ridding a trap of beetles, the old bait was removed and replaced by another, assigned at random. Thus, although a bait was present on a trap for nearly 24 hours, beetle flight occurred almost entirely between noon and dark when temperatures were favorable. Tests were not conducted on stormy days or when air temperature did not reach approximately 65° F.

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1971. Comparative attraction of Douglas-fir beetles to frontalin and tree volatiles, USDA Forest Serv. Res. Pap. INT-99, 16 p., illus.

Female beetles in stems attracted more Douglas-fir beetles than did frontalin and tree volatiles. However, addition of frontalin synergized the response of Douglas-fir beetles to tree volatiles and attracted more males. Response by other bark beetles and predators did not differ significantly by treatment but sex ratios of some species favored females.

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Table 3.--*Analysis of variance of total number of Douglas-fir beetles caught by baited traps at Boise Basin Experimental Forest, 1970*

Source	df	S.S.[2]	M.S.	F
Squares	1	43.540	43.540	43.453**
Periods/square	4	13.084	3.271	.264
Locations/square	4	47.156	11.789	11.765**
Groups of attractants	2	68.394	34.197	34.129**
Error (a)	6	6.015	1.002	
Treatments per group	27	157.383	5.829	6.[illegible]**
Error (b)	135	112.550	.834	
K/location/square[1]	3	60.318	1.117	1.734*
Error (b')	81	52.177	.644	
Total	179	448.122		

[1]Variation from individual trap (K) position within a location within a square after adjustment for treatment and group.

[2]Sums of squares are based on the $\log_e$ (total number beetles + 0.5).

*Significant at the 0.05 level of probability.

**Significant at the 0.01 level of probability.

Results and Discussion

PURITY OF MONOTERPENES

Host tree-produced monoterpenes appear to have two roles in bark beetle attraction; some synergize the attractiveness of pheromones while others may mask their attractiveness. In either case, presence of unwanted monoterpenes as contaminants might affect results. Gas chromatograms of the commercial monoterpenes used in our tests indicated the presence of appreciable amounts of impurities in all but camphene and limonene. Retention time of limonene was greater than anticipated (similar to terpinolene), but the manufacturer confirmed that a sample from the same batch was limonene. Impurities in the α-pinene included camphene and β-pinene; interestingly, these two chemicals occurred in proportions similar to raw Douglas-fir wood resin (Hanover and Furniss 1966). The β-pinene appeared to have minor amounts of α-pinene, camphene, and probably myrcene. The 3-carene had appreciable amounts of impurities (confirmed by the manufacturer), retention times of which indicated presence of α-pinene, β-pinene, myrcene (mostly), limonene, and an unknown. The myrcene appeared to contain some camphene and β-pinene.

The purity as labeled by manufacturer is followed by our determination of purity: α-pinene (90-73), camphene (99-98), β-pinene (95-92), myrcene (96-91), 3-carene (96-73), and limonene (98-95). We did not assess the effect of impurities on response of beetles to these materials during our tests.

RESPONSE OF DOUGLAS-FIR BEETLES

The kinds and relative abundance of scolytids and predators caught by traps are shown in table 4. The Douglas-fir beetle was the most abundant species caught, followed by *Ips pini* (Say), *Hylastes* spp., *Enoclerus sphegeus* Fab. and *Dendroctonus valens* Lec., which are discussed later.

Table 4.--*Species and numbers of beetles caught by sticky traps, combined treatments*

Species	Number ♀	Number ♂	Total
Dendroctonus pseudotsugae Hopk.	621	1,295	1,916
Predators			
Enoclerus sphegeus (Fab.)	133	180	313
Temnochila virescens chlorodia (Mann.)	17	14	31
Thanasimus undatulus Say	11	7	18
Other bark beetles			
Ips pini (Say)	221	208	429
Dendroctonus valens Lec.	71	111	182
Hylastes nigrinus (Mann.)	70	85	155
Hylastes macer Lec.	75	53	128
Hylurgops porosus (Lec.)	77	9	86
Hylurgops n.sp.	47	8	55
Hylastes gracilis Lec.	16	14	30
Pityogenes carinulatus (Lec.)	10	12	22
Orthotomicus latidens (Lec.)	4	12	16
Hylurgops subcostulatus (Mann.)	11	1	12
Hylurgops ruber Sw.	9	1	10
Pityopthorus confinis Lec.	5	5	10
Dendroctonus brevicomis Lec.	3	4	7
Pseudohylesinus nebulosus (Lec.)	4	3	7
Gnathotrichus retusus (Lec.)	4	2	6
Hylastes longicollis Sw.	3	3	6
Scolytus fiskei Blackman	4	2	6
Scolytus unispinosus Lec.	2	1	3
Orthotomicus caelatus (Eichh.)	1	1	2
Trypodendron lineatum (Oliv.)	1	1	2
Dendroctonus ponderosae Hopk.	1		1
Hylurgops rugipennis (Mann.)	1		1
Ips emarginatus (Lec.)	1		1
TOTAL	1,423	2,032	3,455

Catch by Treatments

Numbers of Douglas-fir beetles caught by treatment, date, and sex are shown in table 2. The response of beetles to treatment differed markedly. Group I treatments (resin and monoterpenes) caught one-eighth as many beetles as Group II treatments (frontalin added to resin and monoterpenes). Comparison with the catch of frontalin alone (see Group III treatments, table 2) indicates that a synergistic effect occurred when frontalin was combined with resin or some of its constituent monoterpenes. The most attractive of these combinations was frontalin and resin followed by frontalin and α-pinene. Curiously, frontalin and camphene, reported by Pitman and Vité (1970) to be nearly seven times more attractive than 25 female beetles feeding in Douglas-fir log sections, were less attractive than all but one of the other Group II treatments. When deployed among our Group III treatments (including a ♀ log) frontalin and camphene caught the second highest number (69) of beetles during one replication (June 2), but the total trapped (84) was still significantly less than the other combinations of Group III. However, by testing that particular ♀ log in another area the next day, we confirmed that it had lost most of its attractiveness. Lack of competition from an attractive ♀ log seems involved in the relatively high catch (mostly males) by frontalin and camphene on June 2.

Outstanding among treatments was the total catch by ♀ log traps which was nearly 4 times that of frontalin plus resin and nearly 7 times that of frontalin plus α-pinene, the second and third best treatments, respectively. We interpret this to indicate that the ♀ logs contained attractants not included in our other treatments. That is, even raw resin plus frontalin apparently lacked some attractants contained in the ♀ logs. We suspect that the additional attractants in the logs are contributed by the ♀ beetles, rather than their host. The presence of additional pheromones has also been inferred by Pitman and Vité (1970).

Sex Ratios of Beetles

Approximately equal total numbers of ♂ and ♀ beetles were attracted to resin and its monoterpene constituents (table 2, Group I treatments). Addition of frontalin to those materials (Group II) resulted in an overall male/female ratio of about 2:1. When ♀ logs were present among the treatments (Group III), the sex ratios of beetles responding to comparable treatments involving frontalin were generally higher, attaining 4:1 for frontalin and resin (No. 22, table 2). These results differ from those of Pitman and Vité (1970) who reported generally more females responding.

Compiled in table 5 are total numbers of Douglas-fir beetles and ratios of males to females attracted to resin or monoterpenes alone, and with frontalin added. These data differ from table 2 by including six additional replications of some treatments that were set out in competition with ♀ logs. The male/female ratios without frontalin and with frontalin were 1.2 and 2.7, respectively.

Numbers of beetles and sex ratios for six groups of treatments have been extracted from table 2 and appear in table 6. Sex ratios scale upward from near one for resin and monoterpenes alone to four for frontalin alone. Mixtures of the two attracted intermediate sex ratios.

Catch by Date

We examined felled trees for new beetle attacks, and then began our tests soon after beetles began emerging and flying. Maximum air temperatures and number of beetles caught by date are shown in table 7. Had all treatments been replicated daily at each location, numbers of beetles and air temperatures might have been correlated better.

Table 5.--*Sex ratios of Douglas-fir beetles attracted to resin and monoterpenes alone and with frontalin*

Treatment	Number and sex of beetles			
	Resin or monoterpenes alone		Frontalin added	
	Number	♂/♀	Number	♂/♀
Resin	4	1	391*	2.8
α-pinene	14*	2.5	219*	2.6
Camphene	12*	.7	89*	4.9
β-pinene	6	.5	18	2.6
Myrcene	4	3	20	1.2
3-carene	3	.5	5	1.5
Limonene	9	2	31	1.4
Mix. A[1]	4	All ♂	13	3.3
Mix. B[1]	5	.25	15	1.5
Mix. C[1]	2	All ♀	13	All ♂
Total or average	63	1.2	814	2.7

[1]See table 2 for composition of mixtures.

*12 replications; others, 6 replications.

Table 6.--*Sex ratios of species that were caught in greatest abundance by treatment*

Treatment	Trap days	Douglas-fir beetle		*Enoclerus sphegeus*		*Dendroctonus valens*		*Ips pini*	
		Number	♂/♀	Number	♂/♀	Number	♂/♀	Number	♂/♀
Resin	6	4	1	20	1	8	1	39	1.3
Monoterpenes (6)	66	59	1.2	126	1.1	58	1.1	129	1.0
Frontalin	6	20	4	7	6	1	1	33	.9
Resin & frontalin	6	391	2.8	15	1.1	6	2	27	.9
Monoterpenes (6) & frontalin	84	611	2.6	126	1.9	106	1.9	182	.8
♀ log	6	828	1.6	7	.75	3	2	3	.5
Check	6	0	--	12	1.0	0	--	16	1.7
Total	180	1,913	2.1	313	1.4	182	1.6	429	.9

Table 7.--*Relationship of maximum air temperature and number of Douglas-fir beetles trapped*

Date	Air temperature		Douglas-fir beetles caught	
	Idaho City 3,900 ft.	Location 2 4,100 ft.	Location 2	All areas
	- - - - - - °F. - - - - - -			
May 21	70	65	3	44
22	74	69	320	328
24	72	69	51	74
25	78	74	15	508
26	77	72	195	515
June 2	84	80	322	447

Table 8.--*Number of Douglas-fir beetles caught by treatment in*

Treatment	Delivery system: Polyethylene	Delivery system: Glass vials in
α-pinene	6	8
α-pinene + frontalin		116
Camphene		
Camphene + frontalin		84
α-pinene-camphene, frontalin		
Resin + frontalin	181	210
Total		515

Delivery System and Source of Attractants

Of the 28 artificial treatments (excluding the ♀ log and the check), 22 were delivered in polyethylene plastic stoppers; six were delivered in glass vials inside glass jars with perforated lids. Both delivery systems shared six treatments in common (see table 8).

Numbers of beetles caught were comparable with either delivery system. Although the glass vials seemed better for camphene and frontalin together, the difference may be due to some other factor. In subsequent tests, choice of delivery system should be dictated by practical considerations such as risk of breakage, spillage, and convenience. A screwcap polyethylene container would avoid leakage that occurred around the lid of some of the polyethylene bottle stoppers.

RESPONSE OF PREDATORS

Response by Treatment

Relatively few *Thanasimus undatulus* and *Temnochila virescens* were caught (table 9). Their numbers and sex ratios did not differ significantly by treatment. Most were trapped at Location 2 among felled trees. These two predators may have become more abundant after completion of our tests. This seems especially true of *T. undatulus* which one of us (Schmitz) is studying intensively.[2] In any case, our results do not indicate that any of the treatments are important in the aggregating mechanism of these predators.

[2]For doctoral thesis: The biosystematics of the North American species of *Thanasimus* Latreille (Coleoptera: Cleridae).

Table 9.--*Number and sex of* Thanasimus undatulus *and* Temnochila virescens *caught by treatment and date, Boise Basin Experimental Forest, Idaho, 1970*

Treatment[1]	May 22			May 24			May 25			June 2			Total		
	♀	♂	Σ	♀	♂	Σ	♀	♂	Σ	♀	♂	Σ	♀	♂	Σ
Thanasimus undatulus															
Frontalin + Mix. D	3	2	5					1	1				3	3	6
3-carene	1		1										1		1
Frontalin + β-pinene				1	1	2							1	1	2
Frontalin + α-pinene					1	1				2		2	2	1	3
Frontalin + camphene										2	2	4	2	2	4
Frontalin + resin										1		1	1		1
Frontalin + limonene										1		1	1		1
TOTAL	4	2	6	1	2	3		1	1	6	2	8	11	7	18

Treatment	May 25			May 26			June 2			Total		
	♀	♂	Σ	♀	♂	Σ	♀	♂	Σ	♀	♂	Σ
Temnochila virescens												
Mix. A		1	1								1	1
β-pinene	1	1	2							1	1	2
Limonene	3		3							3		3
Frontalin + α-pinene				1	1	2				1	1	2
Frontalin + myrcene				1		1				1		1
Frontalin + Mix. D								2	2		2	2
Camphene							6	3	9	6	3	9
♀♀ log								2	2		2	2
Check								2	2		2	2
Frontalin + camphene							3	2	5	3	2	5
Frontalin + resin							2		2	2		2
TOTAL	4	2	6	2	1	3	11	11	22	17	14	31

[1]See table 2 for composition of mixtures.

The number of trapped *Enoclerus sphegeus* held relatively constant throughout the tests (table 10). Little difference is apparent in their numbers caught by treatments. Sex ratio favored males in most treatments, especially those involving frontalin. Test location had a pronounced effect on catch (table 11). Location 2 accounted for 97 percent of all *E. sphegeus* caught. As noted previously, this area was uniquely different from the others by having been logged the previous winter. Among the traps were scores of merchantable ponderosa pine and Douglas-fir logs under attack by numerous bark beetles and wood borers before and during the tests. The down trees and insects infesting them apparently contributed somehow to the presence of this clerid.

Table 10.--*Number and sex of* Enoclerus sphegeus *caught by treatment, Polar Bear Lake Recreation Area, Utah, 19*

Treatment[1]	May 21			May 22			May 24			May 25			May 26			June 2			Total		
	♀	♂	Σ	♀	♂	Σ	♀	♂	Σ	♀	♂	Σ	♀	♂	Σ	♀	♂	Σ	♀	♂	Σ
GROUP I																					
1. Camphene	1	2	3							1	2	3							2	4	6
2. Limonene	7	2	9							3	6	9							10	8	18
3. α-pinene	8	8	16							8	5	13							16	13	29
4. β-pinene	3	3	6							1	4	5							4	7	11
5. Mix. B	1	1	2							4	7	11							5	8	13
6. Resin	2		2							8	9	17				1	1		10	10	20
7. Myrcene	2	1	3							4	3	7							6	4	10
8. Mix. A	1		1							2	5	7							3	5	8
9. 3-carene	2	1	3							1		1							3	1	4
10. Mix. C	1	1	2							3	1	4							4	2	6
TOTAL	28	19	47							35	42	77				1	1		63	62	125
GROUP II																					
11. Frontalin + resin							1	1	2	1		1		3	3				2	4	6
12. Frontalin + α-pinene								3	3				2			1		1	3	8	11
13. Frontalin + limonene							4	3	7		1	1	3	6	9				7	10	17
14. Frontalin + myrcene							2		2				1	3	4				3	4	7
15. Frontalin + β-pinene							2	3	5	1		1	2	4	6				5	9	14
16. Frontalin + Mix. B							1	3	4				2		2				3	3	6
17. Frontalin + Mix. C							9	2	11										9	2	11
18. Frontalin + Mix. A							2	2	4		1	1							2	3	5
19. Frontalin + camphene								1	1					1	1					2	2
20. Frontalin + 3-carene							1	7	8		1	1							1	8	9
TOTAL							22	25	47	2	3	5	7	14	21	1	1		32	43	75
GROUP III																					
21. 50 ♀♀ log				3	1	4										1			4	1	5
22. Frontalin + resin				1		1													1		1
23. Frontalin + α-pinene					3	3										1		1	1	3	4
24. Frontalin + Mix. D		1	1		2	2				1		1							1	3	4
25. Frontalin + Mix. D																1	1		1	1	2
26. Frontalin + camphene				2	6	8													2	6	8
27. Frontalin																1			1		1
28. α-pinene					3	3														3	3
29. Camphene				2	9	11										1			3	9	12
30. Check				3	5	8													3	5	8
TOTAL		1	1	16	29	45				1		1				5	1	1	22	30	52
GRAND TOTAL	28	20	48	16	29	45	22	28	47	38	45	83	7	14	21	7	2	1	118	138	256

[1]See table 2 for composition of mixtures and sources of supply.

Table 11.--*Numbers of the most abundant species caught, by location*

Location[1]	Trap days	Douglas-fir beetle	*Enoclerus sphegeus*	*Dendroctonus valens*	*Ips pini*
1	3	318	6	5	1
2	6	906	303	172	428
3	3	620	3	3	1
4	3	40			
5	3	32	1	2	
Total		1,916	313	182	430

[1]See table 1.

RESPONSE OF OTHER BARK BEETLES

Eleven genera and 24 species of bark beetles were caught (table 4). Besides the Douglas-fir beetle, six species merit discussion because of their abundance or sex ratios.

Numbers of *Ips pini* were fairly constant by sex and treatment groupings (tables 6, 12). It was abundant only in Location 2, probably because its host, ponderosa pine, was felled among the traps there. Only two specimens were caught elsewhere. Further, it was the most abundant species caught on the check traps. We see no apparent involvement of any of our treatments in its aggregation. The low catch by traps baited with ♀ logs indicates that they may have repelled *I. pini*.

Numbers of *D. valens* caught by treatments did not differ significantly. However, treatments involving frontalin attracted generally more males than females and no beetles were caught by check traps. Similarity of these results to those of the Douglas-fir beetle indicate that a low level attraction may have occurred.

The next most abundant species were *Hylastes nigrinus* and *Hylastes ruber*. Their sex ratios did not differ. However, significantly more females were caught of the next two most abundant species, *Hylurgops porosus* and *Hylurgops* n.sp. They were not attracted by any particular treatment, except for *Hylurgops* n.sp. On May 21, 17 female *Hylurgops* n.sp. were caught by a trap baited with a ♀ log. The catch of *Hylurgops* n.sp. on other traps during the test never exceeded four, usually only one or two were caught, if any.

Conclusions

We infer from these tests that frontalin and resin (including some of its monoterpenes, especially α-pinene) are important, but they are not the only components of the aggregating mechanism of *D. pseudotsugae*. Baiting of live trees with any of the more productive treatments will likely induce attacks by wild beetles which themselves add attraction and cause mass attack. However, use of baited mechanical traps of any sort for control would be enhanced by additional naturally occurring attractants, not yet identified. These attractants are presumed to be pheromones rather than host volatiles.

Comparison of catches of *D. pseudotsugae* and its beetle predators indicates that the aggregating mechanism of the former is more specific to it than its enemies. Deployment of such specific attractants for control of the Douglas-fir beetle may leave predators relatively unscathed to carry on their work of controlling beetles that fail to be trapped.

Table 12.--*Number and sex of [illegible] Experimental Forest, 1970*

Treatment[1]	*Dendroctonus*					
	♀	♂		♀	♂	
GROUP I						
1. Camphene	2	1	3	–	–	–
2. Limonene	3	4	7		3	3
3. α-pinene	1	1	2	5	5	10
4. β-pinene	2	3	5	12	9	21
5. Mix. B	4	3	7	2	3	5
6. Resin	4	4	8	17	22	39
7. Myrcene	3	1	4	4	4	8
8. Mix. A	6	2	8	5	5	10
9. 3-carene				4	4	8
10. Mix. C	4	6	10	21	20	41
TOTAL	29	25	54	72	77	149
GROUP II						
11. Frontalin + resin	1	2	3	7	8	15
12. Frontalin + α-pinene		2	2		1	1
13. Frontalin + limonene	2	2	4	17	19	36
14. Frontalin + myrcene	6	14	20	6	6	12
15. Frontalin + β-pinene	4	10	14	1	3	4
16. Frontalin + Mix. B	3	8	11	5	6	11
17. Frontalin + Mix. C		5	5	17	6	23
18. Frontalin + Mix. A	2	4	6	8	3	11
19. Frontalin + camphene	1	1	2	6	1	7
20. Frontalin + 3-carene	7	7	14	5	6	11
TOTAL	26	55	81	72	59	131
GROUP III						
21. 50 ♀♀ log	1	2	3	1	2	3
22. Frontalin + resin	1	2	3	7	5	12
23. Frontalin + α-pinene	2	1	3	15	6	21
24. Frontalin + Mix. D	2		2	4	5	9
25. Frontalin + Mix. D	4	10	14	6	7	13
26. Frontalin + camphene	3	6	9	12	11	23
27. Frontalin		1	1	17	16	33
28. α-pinene	1	2	3	4	3	7
29. Camphene	2	7	9	5	7	12
30. Check				6	10	16
TOTAL	16	31	47	77	72	149
GRAND TOTAL	71	111	182	221	208	429

[1]See table 2 for composition of mixtures and sources of supply.

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USDA FOREST SERVICE
RESEARCH PAPER INT-97
1971

INVESTIGATION OF SLOPE FAILURES IN THE IDAHO BATHOLITH

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USDA Forest Service
Research Paper INT-97
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ABSTRACT

Precipitation events in the winter and spring of 1965 caused significant erosion and numerous landslides in many parts of the Idaho Batholith. Most slope failures were associated with roads. An investigation of several representative failures in the Zena Creek sale area on the Payette National Forest was conducted. Details of the field and laboratory tests are given, and three examples of the stability analyses are presented. Causes of the failures are discussed and recommendations for future construction in similar terrain are made.

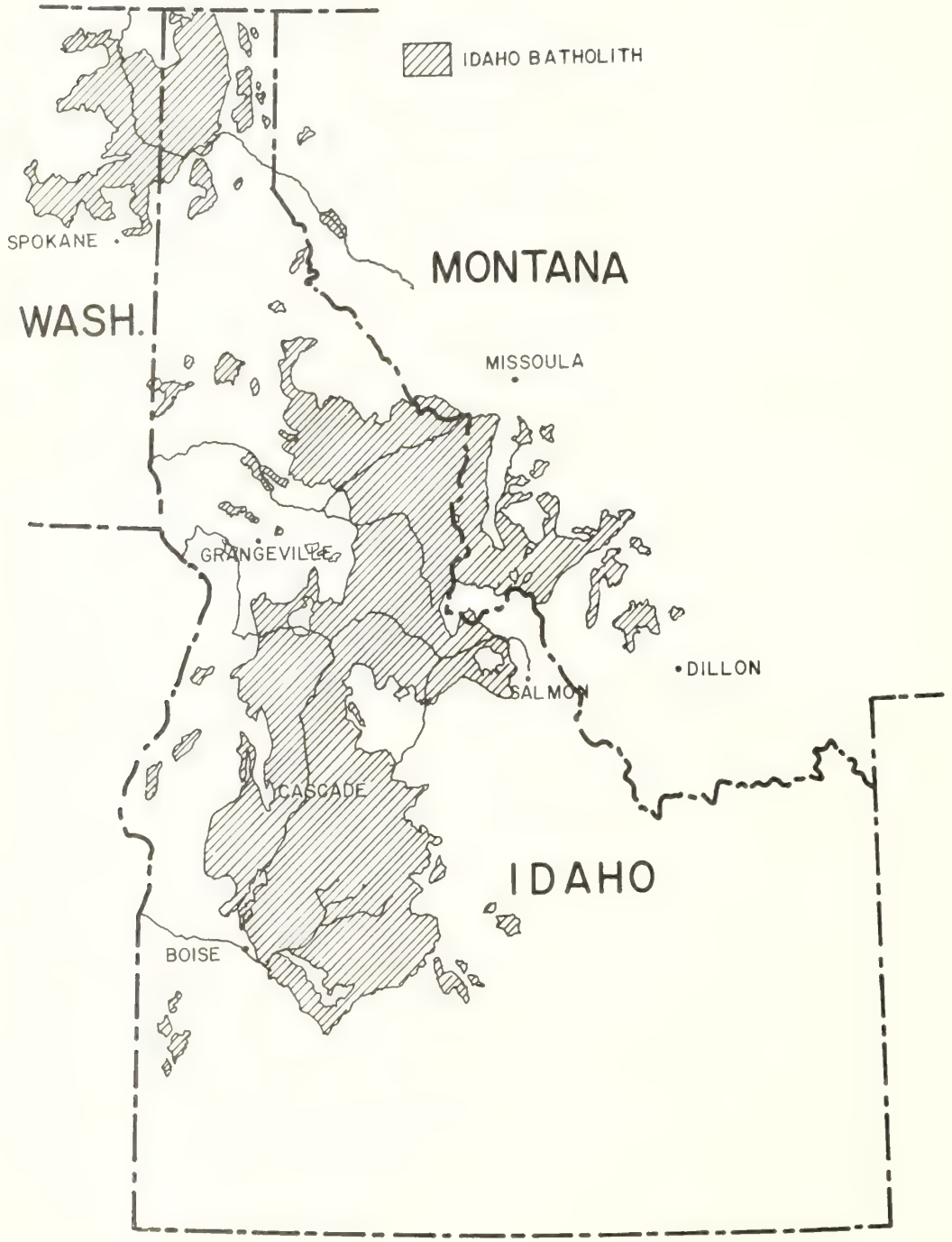

Figure 1.--The Idaho Batholith.

Introduction

As the uses of forest lands increase, the necessity to develop less favorable terrain also increases. It also becomes more difficult and complicated to provide access that is both economical and safe from contributing to watershed damage.

Because of the increased and justified emphasis upon environmental degradation, proper use of the many millions of acres of forest watersheds requires careful planning. The skills of many disciplines and the combined knowledge that covers all aspects of this complicated ecosystem--the forest--are necessary to assure proper use of forest lands. The silviculturist, ecologist, hydrologist, engineer, and others, must all function as a team to develop and carry out plans for management of forest lands.

The Idaho Batholith (fig. 1) is one of the most critical areas as to surface and subsurface stability (i.e., erosion and landslides) in the Intermountain West; also, this area provides prime spawning and rearing grounds for the Pacific salmon, good timber-producing land and outstanding recreation opportunities. Two major spawning rivers are the South Fork of the Salmon and the Selway Rivers.

The Batholith contains some of the most rugged and pristine scenery in America and includes such well-known areas as the Selway-Bitterroot Wilderness Area, Salmon River Breaks Primitive Area, and the Magruder Corridor. In such areas, those who are charged with the responsibility of multiple use land management face their most serious and complicated challenges. Within the scope of present knowledge and technological skill, proper planning can assure many uses for much of this vast land area. However, much of the Batholith must wait for the results of research to provide additional management guidelines, and it may have to be managed for less than total resource potential if adequate environmental safeguards are to be applied.

Considerable attention is currently being directed to the Batholith area. It contains valuable timber reserves as well as other resources which are important to the regional and national economies. However, many of its steep slopes are highly erodible and susceptible to landslides. More specifically, slopes are often greater than 60 percent and are commonly composed of highly fractured and weathered granite overlain by thin layers of loose, cohesionless soils. Developmental activities, especially roadbuilding, increase the occurrence of landslides and provide large exposed areas from which sediment can readily be removed by normal erosional processes. Initial increases in production of sediment have been measured and in some instances were more than a thousandfold greater than natural rates from undisturbed terrain.

The most serious consequence of this accelerated sedimentation is believed to be destruction of aquatic habitat, especially of the spawning and rearing areas of anadromous fish (fig. 2). In addition, the silting of downstream reservoirs is an important consideration, as is the visual impact of exposed cutbanks, fill slopes, debris piles, and slide scars.

This paper describes an investigation of slope failures in one small area of the Batholith and the conclusions and recommendations derived therefrom.

Figure 2.--Krassell Hole, Secesh River.

Road Location and Design Concepts

Traditionally, the concepts of road location and design have stressed the economics of transportation from origin to destination. This has encompassed not only the cost of the facility (fixed cost, depreciation, and maintenance) but also the cost to the user (principally concerned with speed of travel). More sophisticated analyses are evolving as more of the impacts of location and design are considered. However, this evolution has not generally developed on forest roads. Methods of analysis that could be helpful in evaluating effects of all major factors are available, but usually the inputs are not. For example, we do not have accurate values, nor in most cases, any value to assign to the influence that erosion may have on the functioning of the total system (ecosystem). Instinctively, from our ocular estimates, and in some instances from quantitative measurements of damage from erosion, we know that we must improve our present practices. Fortunately (or unfortunately, when viewed from its lack of use in the past), we are close to having sufficient technical knowledge to accomplish this objective.

To help illustrate what can be done and how it is done in areas such as the Idaho Batholith, information from a recent research study of logging roads in the Zena Creek drainage (tributary to the Secesh and South Fork Salmon Rivers) on the Payette National Forest will be used (figs. 3a and 3b).

Zena Creek Experimental Logging Study

In 1957, Region 4 (Intermountain) of the USDA Forest Service began a study of logging methods that could be used for harvesting timber on some of the steep slopes of the Batholith. The basic objective of the study was to determine if logging could be carried out economically without unacceptable damage to the watersheds. Tractors, jammers, and portable towers (skyline systems) were used for skidding timber during the study. In general, it was concluded that logging the steeper slopes with skyline systems caused little damage to the watershed and that the cost of logging, although high, still wouldn't prevent a logging operator from making an acceptable profit.

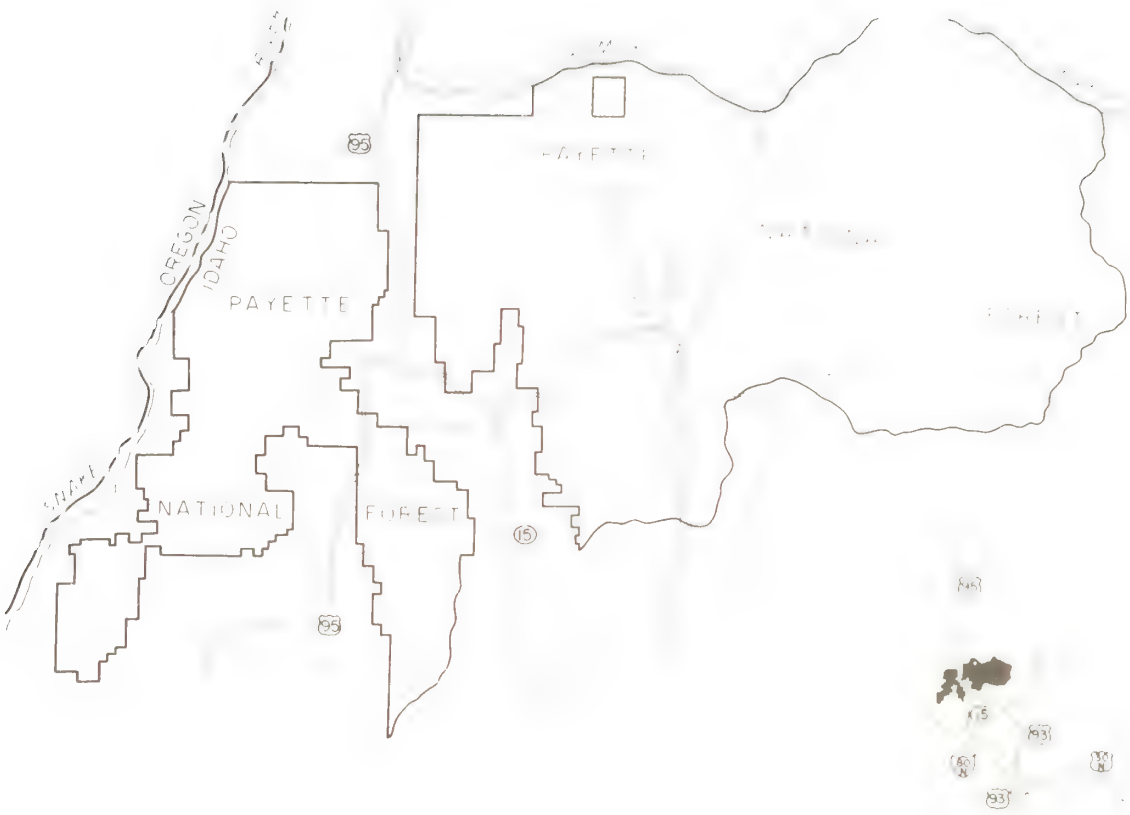

Figure 3a.--Location of Zena Creek in the Payette National Forest.

Figure 3b.--Oblique photograph of Zena Creek terrain illustrating its rugged and steep topography.

In the December-January 1964-65 period and in April of 1965, climatic events occurred that resulted in extensive damage to the road system. The probable frequency of these events is not well established. However, it can be concluded from past weather records that such events could happen as often as once in five years.

During late December and early January of 1964-65, over 6 inches of precipitation (mostly snow) fell in the Zena Creek area. Some road failures occurred below 5,000 feet as a result of this storm. Then, on April 19, 1965, 1.03 inches of rain fell. In the areas below about 4,200-foot elevation, where snowmelt had already been completed, little damage occurred. In areas where elevations were between 4,200 and 5,500 feet and the snowmelt was intense, extensive damage occurred, primarily to road fills.

The major landslides and erosion on the watersheds in the Zena Creek drainage were judged to have resulted from road construction. The balance of this report will deal primarily with the road systems that were constructed to transport timber from the Zena Creek drainage.

In figure 4, a planimetric map of the Zena Creek drainage shows the road system used to gain access to the harvest area. The arrows and circled points mark locations of sites that were investigated as part of the Zena Creek study. The Secesh River is a tributary to the South Fork of the Salmon River, as previously noted.

Failure Investigations

The major purpose of these investigations was to determine the principal causes of slope failures, both road-associated and nonroad-associated, in the Zena Creek study area. Surface erosion, or the movement of single grains by wind and water, was excluded from consideration except where this type of movement contributed to mass failures. Whether surface erosion by runoff is an important mode of soil detachment is a matter for study. Nevertheless, the importance of surface water as a transporting medium is well recognized, and movement of soil particles in roadside ditches and ephemeral channels takes place readily at Zena Creek.

Raveling from weathered rock surfaces in cut slopes was also excluded from this investigation. This, too, is recognized as an important contributor of soil grains to surface water in roadside ditches.

The analysis of surface erosion remains a highly empirical art, and is beyond the scope of this study. Only the movement of soil *en masse* was considered.

FIELD AND LABORATORY TESTS

A detailed discussion of the field and laboratory tests and the results thereof may be found in the original report.[1] The procedures followed were relatively routine for an engineering investigation of this type, and only the more significant findings will be discussed herein.

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[1]R. B. Gardner, M. J. Gonsior, and G. L. Martin. Zena Creek road and logging system investigation. September 1969, 173 p., illus. (Unpublished report on file at USDA Forest Serv., Intermountain Forest and Range Exp. Station, Forestry Sciences Lab., Bozeman, Montana.)

Figure 4.--Planimetric map, Zena Creek Road.

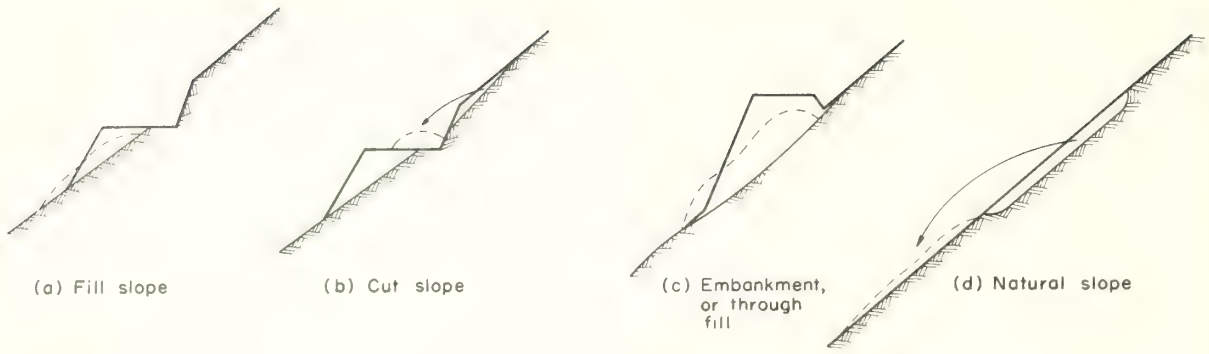


Figure 5.--Failure types.

A preliminary reconnaissance of the Zena Creek study area was made in May of 1967 to identify the extent and types of failures that occurred during the previously discussed 1965 storm event. As a convenience for analysis and discussion, four general failure types were identified, as shown in figure 5.

Based upon the preliminary reconnaissance, eight sites representing the three failure types shown in figure 5(a), (b), and (d) were selected for intensive study (i.e., fill-, cut-, and natural-slope failures, respectively). None of the embankment failures (c) were deemed amenable to analysis, but one stable embankment was selected for sampling and analysis. In addition, four other sampling sites were chosen for analysis of material properties representative of alluvial and bank slough deposits. All 13 sites are identified and briefly described in figure 4 and table 1.

During the months of July and August of 1967, sampling, field testing, and mapping were conducted at the selected sites.

Seismic subsurface exploration was conducted at each of the failure sites and also at the site of the stable embankment. In addition, some verification work was performed by trenching with a tractor-mounted backhoe. Representative, disturbed samples were obtained by manual excavation, some with the aid of the backhoe. Depths, sizes, and other descriptions of these samples are given in table 2. In-place density tests were performed with a balloon volumeter; these results are also shown in table 2. Finally, the geometry at each of the sites was mapped and photographs were taken.

Laboratory tests were performed to determine grain-size distribution, liquid limits, and plastic limits for classification purposes. Results of these tests are given in table 3. For the material passing the 3/8" sieve, the gradations of all samples, excluding samples which were obtained from alluvial or slough deposits, were within the range shown by dashed lines in figure 6. Further, the extremes represented by the dashed lines represent two samples obtained only 20 feet apart in natural soil. The gradations of all other samples, representing both fills and natural deposits and representing a wide range of other conditions, were within the range shown by the solid lines in figure 6. Because these materials are easily broken down, and thus the sieve analyses are subject to error simply from variations in abrasive action during preparation and testing, the variabilities in grain-size distributions for samples passing the 3/8" sieve were judged negligible.

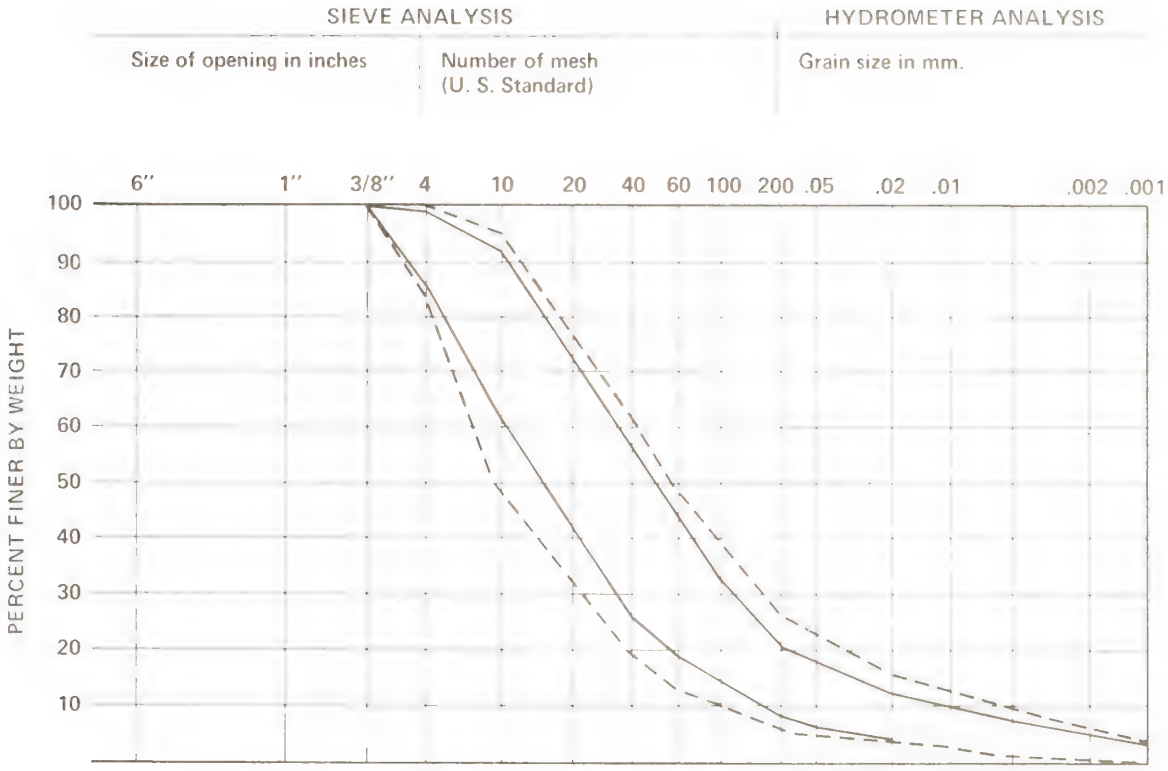

SIEVE ANALYSIS
HYDROMETER ANALYSIS
Size of opening in inches
Number of mesh (U. S. Standard)
Grain size in mm.
6" 1" 3/8" 4 10 20 40 60 100 200 .05 .02 .01 .002 .001
100 90 80 70 60 50 40 30 20 10
PERCENT FINER BY WEIGHT

Figure 6.--Gradation curves,-3/8" materials.

Table 1.--[illegible]

Site	Failure type and/or description
917-1	Embankment section in small gully, not a failure
917-2	Cut-bank slough deposit in roadside ditch
917-3	Incipient fill-slope failure
917-4	Cut-slope failure
917-5	Alluvial deposit in streambed
917G-1	Combination fill- and cut-slope failure
917H-1	Fill-slope failure and incipient fill-slope failure
917H-2	Fill-slope failure
917H-3	Cut-slope failure, may also be considered natural-slope failure
977-1	Natural-slope failure
977-2	Fill-slope failure
977-3	Cut-bank slough deposit, saturated by natural spring
977-4	Alluvial deposit on road surface

Table 2.--*Sample descriptions and field test data*

Sample no.	Sample weight (lb.)	Depth (ft.)	In-place γ_t (p.c.f.)	w (%)	e***	**** Relative density (%)
917-1-1†	30	1.0	102.4	2.3	0.65	79
917-1-2	31	1.0	102.2	4.4	.69	77
917-1-3	32	2.5_F	98.3	6.5	.79	73
917-1-4	54	2.5_F	126.8	6.1	.38	94
917-1-5	41	2.0	113.1	6.4	.56	83
917-2-1	108	1.0_F	87.4	4.7	.98	66
917-3-1	106	3.5	106.3	8.4	.69	77
917-3-2	47	2.5_F	95.5	3.6	.79	73
917-3-3	47	1.0_F	105.4	2.7	.61	81
917-4-1	29	2.0	107.2	8.1	.67	78
917-5-1	105	1.5	105.8	8.4	.69	77
917G-1-1	30	2.0_F	98.8	3.6	.73	75
917G-1-2	41	1.5_F	108.0	1.3	.55	84
917G-1-3	29	.5	104.8	.6	.59	82
917H-1-1	36	1.0_F	96.2	2.1	.76	74
917H-1-2	102	1.5_F	99.1	5.5	.76	74
917H-1-3	41	1.0	114.4	2.5	.48	88
917H-2-1	30	2.5	117.3	6.5	.50	87
917H-2-2	30	6.0	142.5	5.2	.22	107
917H-2-3	28	2.5_F	**	**	**	**
917H-2-4	30	1.0	104.6	2.4	.62	80
917H-3-1	35	1.5	92.1	2.3	.84	71
917H-3-2	50	1.5	90.0	2.5	.88	69
977-1-1	42	2.5	103.0	4.8	.68	76
977-1-2	28	2.0	128.1	3.2	.33	98
977-2-1	48	6.0	**	**	**	**
977-2-2	42	2.5_F	113.1	3.5	.51	86
977-2-3	41	1.0_F	96.1	1.7	.75	74
977-2-4	70	1.0	95.1	5.8	.84	71
977-3-1	108	.5	102.5	14.2	.84	71
977-3-2	*	.5	130.1	21.1	.54	85
977-4-1	100	.5	102.8	1.7	.64	79

F Indicates fill material.

* Same site as 977-3-1. Increased density and moisture content reflect changes caused by hand-tamping

** Fractured bedrock--too coarse and hard for in-place density and moisture content tests.

*** Void ratio, $e = G_s\ (1+w)\ \frac{\gamma_w}{\gamma_t}$, where G_s = specific gravity of soil particles, γ_w = unit weight of water (62.4 p.c.f.).

**** Relative density, based upon figure 5, $= \frac{\gamma_d}{127\ \text{p.c.f.}} \times 100\%$, where

γ_d = dry unit weight $= \frac{\gamma_t}{(1+w)}$.

γ_t = unit weight of soil-water system.

w = water content relative to dry unit weight.

† Last number identifies sample, first and second numbers identify failure site (e.g., sample no. 917-1-3 indicates sample no. 3 recovered at site 917-1).

Table 3.--*Grain-size distributions and unified and AASHO soil classifications*

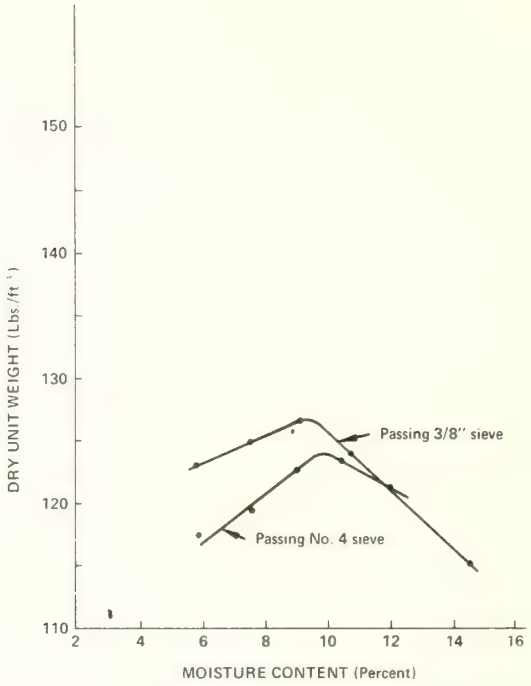
Sample	Cumulative percent passing sieve sizes										Unified	AASHO
	3/8"	#4	#10	#40	#60	#200	.05mm.	.02mm.	.01mm.	.005mm.	.001mm.		
917-1-1	97	91	69	33	25	12.6	11.1	7.6	5.8	4.2	1.8	SW-SM	A-1-b
917-1-2	95	87	63	30	23	12.4	[illegible]	6.3	5.3	3.1	2.0	SW-SM	A-1-b
917-1-3	95	90	68	32	25	12.1	10.0	8.0	6.1	5.0	2.5	SW-SM	A-1-b
917-1-4	71	64	[illegible]	[illegible]	16	6.4	5.6	3.5	2.9	[illegible]	[illegible]	SW-SM	A-1-a
917-1-5	86	78	61	29	21	8.8	[illegible]	4.5	3.6	[illegible]	.8	SW-SM	A-1-b
917-2-1	94	88	72	34	25	11.1	10.4	6.4	5.2	3.7	1.9	SW-SM	A-1-b
917-3-1	90	79	55	31	24	14.4	[illegible]	9.5	8.6	6.5	3.0	SM	A-1-b
917-3-2	95	84	58	32	27	[illegible]	15.4	11.4	[illegible]	4.9	3.0	SM	A-1-b
917-3-3	85	76	56	28	22	12.1	9.4	7.4	5.0	3.3	1.5	SW-SM	A-1-b
917-4-1	97	86	66	[illegible]	[illegible]	12.8	11.6	8.3	7.3	4.7	1.5	SW-SM	A-1-b
917-5-1	94	90	[illegible]	[illegible]	15	2.9	2.4	1.0	[illegible]	.0	.0	[illegible]	A-1-b
917G-1-1	94	90	74	39	31	15.4	11.7	7.8	6.4	3.8	.9	SM	A-1-b
917G-1-2	83	79	66	[illegible]	26	11.7	9.8	4.8	3.8	1.9	.5	SW-SM	A-1-b
917G-1-3	79	72	54	[illegible]	16	6.5	6.1	3.9	2.8	1.9	.0	SW-SM	A-1-b
917H-1-1	93	83	59	[illegible]	17	7.9	7.0	4.5	3.8	[illegible]	.7	SW-SM	A-1-b
917H-1-2	89	80	58	24	16	6.7	5.8	4.5	3.9	2.3	1.2	SW-SM	A-1-b
917H-1-3	84	76	57	27	19	[illegible]	[illegible]	5.0	4.3	[illegible]	..7	SW-SM	A-1-b
917H-2-1	100	100	[illegible]	61	48	26.0	[illegible]	[illegible]	13.1	9.5	3.8	SM	A-2-4
917H-2-2	100	99	92	54	41	20.4	17.4	11.6	9.2	4.8	1.3	SM	A-2-4
917H-2-3	100	84	49	19	[illegible]	[illegible]	5.0	3.8	3.4	2.5	1.1	SW-SM	A-1-a
917H-2-4	85	78	64	[illegible]	[illegible]	9.7	8.0	4.1	3.6	2.0	.7	SW-SM	A-1-b
917H-3-1	91	86	70	[illegible]	28	13.7	[illegible]	8.9	6.8	4.6	2.0	SM	A-1-b
917H-3-2	72	66	50	26	20	10.7	8.9	5.0	4.0	[illegible]	.6	SW-SM	A-1-a
977-1-1	99	95	[illegible]	40	[illegible]	14.4	[illegible]	9.2	6.4	4.5	2.1	SM	A-1-b
977-1-2	91	82	62	30	[illegible]	10.3	[illegible]	5.5	2.8	1.0	.4	SW-SM	A-1-b
977-2-1	87	81	25	10	7	[illegible]	[illegible]	1.8	1.4	.8	.3	[illegible]	A-1-a
977-2-2	96	91	[illegible]	43	34	17.3	12.1	8.7	5.1	3.6	1.0	SM	A-1-b
977-2-3	95	90	[illegible]	[illegible]	25	10.6	7.8	4.6	2.6	1.3	.0	SW-SM	A-1-b
977-2-4	76	69	31	24	18	7.9	6.1	4.2	4.0	2.4	.7	SW-SM	A-1-b
977-3-1	95	90	71	[illegible]	29	15.0	9.7	9.1	4.9	3.5	1.1	SM	A-1-b
977-3-2	95	90	71	38	29	15.0	9.7	9.1	4.9	3.5	1.1	SM	A-1-b
977-4-1	100	97	80	26	14	1.8	1.1	.5	.5	.5	.0	SW	A-1-b

Because of the near identity of all the samples, and because all further testing was to be conducted on only the finer portions of the samples, the remainder of the testing program was confined to determination of the pertinent engineering properties of a single sample from site 917-3. Included were tests to determine moisture-density relationships, shear strength, and permeability.

Results of the moisture density tests, conducted according to AASHO Test Designation T99-57, Method A, except for variations in maximum grain size, are shown in figure 7. Note that for material passing the 3/8" sieve, a maximum dry unit weight of approximately 127 pounds per cubic foot (p.c.f.) was obtained, while for the fraction finer than a #4 sieve, a maximum dry unit weight of approximately 124 p.c.f. was achieved.

Numerous direct shear and triaxial compression tests were conducted to investigate the effects of unit weight and moisture content upon the shear strength of these materials. However, strengths based upon effective stress parameters showed negligible variation over a wide range of conditions. Typical results are shown in figure 8, which represent the Mohr stress circles at failure for consolidated, undrained triaxial tests on saturated specimens wherein pore pressures were measured. These tests were conducted at an axial strain rate of 0.02 inch per minute, and failure was defined as the maximum ratio of major to minor principal effective stress. All tests were conducted on

Figure 7.--Moisture-density test results.



materials passing a #16 sieve, and all specimens were approximately 5 inches in height and 2-1/2 inches in diameter before testing.

Finally, falling head permeameters were used to determine the relationships between void ratio and permeability. Typical results of these tests are shown in figure 9. Unfortunately, tests could not be satisfactorily conducted at void ratios as high as are commonly found in the field, due to channel formation along the smooth walls of the permeameters. Nevertheless, the results indicated that these materials are capable of being relatively impermeable when disintegrated and compacted.

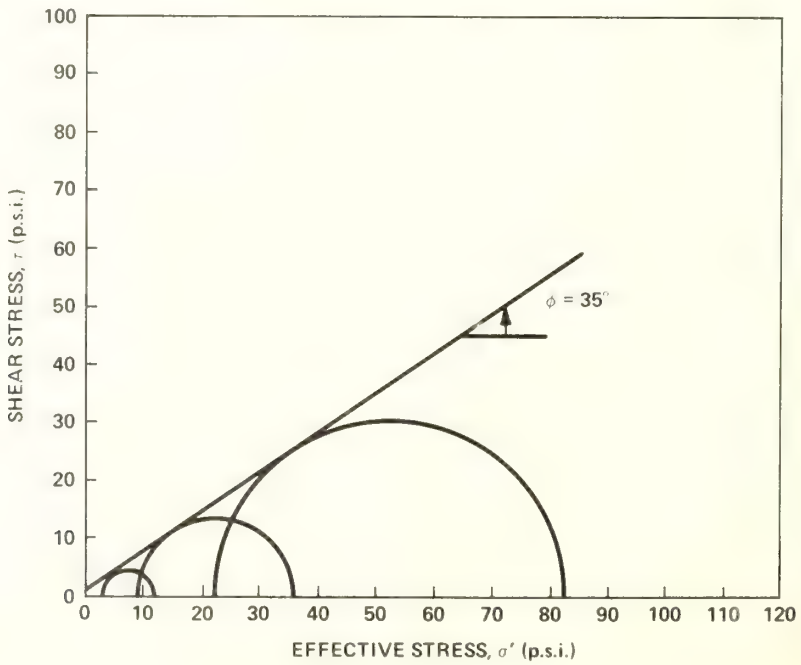


Figure 8.--Mohr stress circles and failure envelope from consolidated, undrained triaxial compression tests.

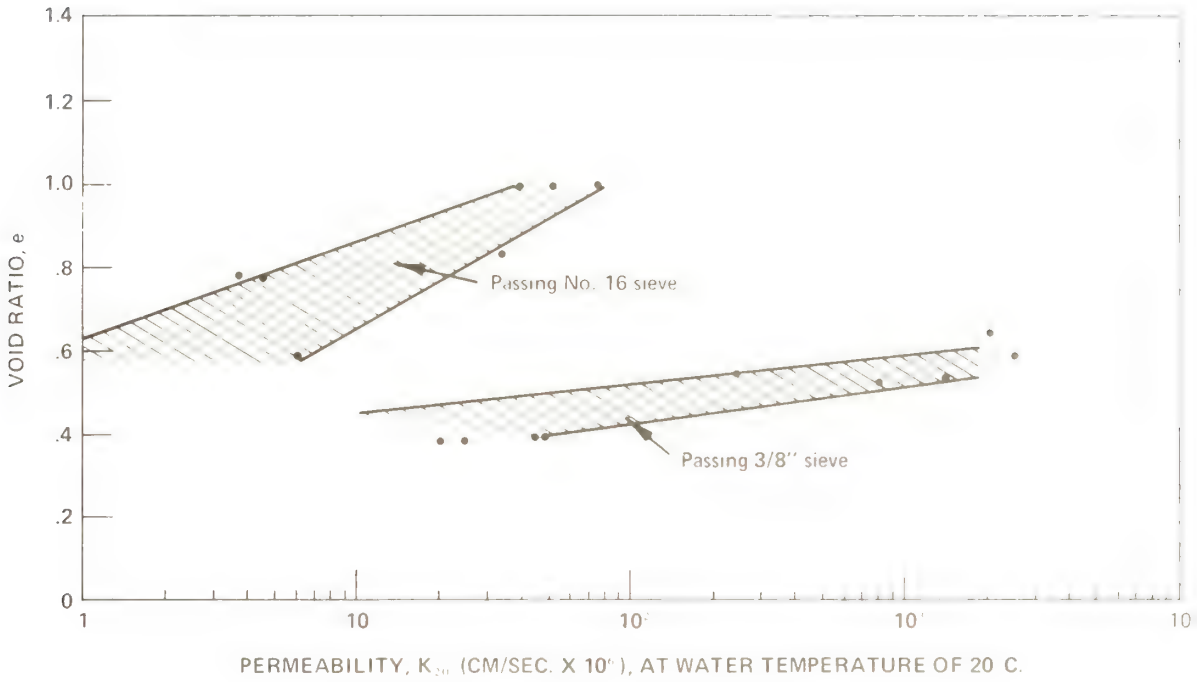


Figure 9.--Permeability test results.

DISCUSSION OF TEST RESULTS

In any investigation of this type, the major objective of the laboratory testing program should be to simulate the actual field conditions as closely as possible. Insofar as available equipment and time permitted, this was done. However, as has been previously indicated, a period of over two years had elapsed between the rain-on-snow event that caused failures at Zena Creek and the beginning of investigation. Erosion and growth of new foliage had significantly altered both the geometry and soil conditions at the failure sites in the interim, and in most cases hardly any traces of the original material remained at or near the sites. Furthermore, fabrication of samples of this material in the laboratory at densities as low as are found in the study area was an extremely difficult task and often met with failure. Thus, in regard to the tests and their results, considerably more work must be done to fully describe these materials and to establish adequate criteria for the design of stable roads and safe harvesting practices in the Zena Creek and similar areas.

For design purposes in this area, it appears that reasonable values are 35° and 0 for the angle of internal friction (ϕ) and cohesive strength (c), respectively. These values are based upon the results of the triaxial compression tests, some of which are shown in figure 8. Although the strength envelopes indicated slight cohesive strength in most of the tests on saturated specimens, it is doubtful that any permanent cohesion can be assumed for long-term design purposes. Further, in most cases, it is believed that some of the apparent cohesion measured in the triaxial tests on saturated specimens could be accounted for by corrections for membrane resistance; no corrections were made for this factor.

The value of 35° for the friction angle is undoubtedly conservative, but not excessively so. For analyses of the type conducted here, the plane strain test is more suitable for determining strength parameters and for simulating conditions along the failure plane, but the apparatus necessary for conducting such tests was not available. It is

known, however, that the friction angle measured in plane strain tests will be appreciably greater than that determined from triaxial tests on cohesionless materials. Generally, the difference in values depends upon density, and will be found to decrease with decreasing density. Therefore, it can be concluded that 35° is a reasonable lower limit for the value of the friction angle for the materials investigated in this study. (As will be noted from subsequent discussions of the stability analyses, it appears that a value of 38° for the friction angle more nearly complies with the conditions for most of the failures.)

A complete series of tests that would give an accurate determination of the critical void ratio-confining pressure relationship was not conducted; however, volume change measurements from both direct shear and triaxial tests indicated that, for the relatively shallow depths to the failure planes in most cases, the critical void ratio is in the range of from 0.55 to 0.65. The significance of this is discussed more fully in the conclusions of the failure investigations.

Permeabilities in the range from 10^{-6} to 10^{-3} cm./sec. were measured in tests wherein sample size, maximum grain size, and void ratio (density) were varied. Few of these tests adequately simulated the loose conditions and grain-size distributions actually existing in the field, and thus the measured permeabilities are probably lower limits for the actual field conditions. Nevertheless, these materials are capable of good water tightness and due to compaction and rapid disintegration they are undoubtedly continually decreasing in permeability both in road fills and in the natural state. This presumed reduction in permeability over a period of time is important in several ways. First, infiltration capacity is reduced, thus tending to increase overland flow and scour, or erosion; in the absence of vegetation, the damage is many times greater. Second, culverts and other facilities designed to handle surface water based upon reasonably permeable fills at the time of construction may become inadequate in later years as the quantities of surface water increase. Third, for a given quantity of subsurface flow, one or both of two factors must increase in response to a loss in permeability. Either the cross-sectional area of flow must increase, hence the phreatic surface must rise closer to the ground surface, or else the hydraulic gradient must increase, thereby creating higher seepage forces. A further danger from an increase in hydraulic gradient is that of piping, or the washing away of soil at a point of emergence. When this occurs, for example at the toe of a fill slope, the piping action causes removal of soil which is necessary for support of the remaining material upslope, thus leading to possible mass failure.

In connection with the prognosis of this investigation, a comparison of the in-place densities (table 2) and the results of the moisture-density test results (fig. 7) reveal the significant disparity between measured field conditions and the attainable conditions.

STABILITY ANALYSIS

Neither the field and laboratory procedures nor the types of analyses performed in this study were very complex or unique. The ordinary method of slices, assuming circular failure surfaces, was the predominant procedure followed in most of the analyses. A variation of this procedure was programmed for a small digital computer and used for a more thorough search for the critical failure arc for some of the fill slopes; slices of differential thickness were assumed in order to derive a closed-form solution for the safety factor. The infinite slope stability theory, as developed by Taylor,[2] was used to analyze the natural slope failure, and was also applied to some of the shallow

[2]Donald W. Taylor. Fundamentals of soil mechanics. New York: John Wiley & Sons, Inc., 700 p., illus. 1948.

cut-and-fill-slope failures. In addition, a sliding block or wedge analysis was used to analyze some of the cut- and fill-slope failures wherein the failure surfaces could reasonably be considered planar.

To satisfy requirements of completeness and brevity, only three stability analyses are presented and discussed in this paper. Those included were selected primarily for their illustrative value. Complete descriptions of all the sites and analyses may be found in the original report of this investigation.[1]

The reliability of any analysis of the types conducted herein depends upon five fundamental factors:

1. Accurate description of the geometry (i.e., topography and cross section);

2. accurate knowledge of the soil properties (i.e., shear strength and unit weight);

3. correct definition of external loads, if any (e.g., vehicle or structural foundation loads);

4. correct description of ground water or seepage conditions (i.e., pore water pressures); and,

5. correct method of analysis.

As was mentioned previously, there had been significant alterations of the topography during the period between time of failure and time of investigation. Undoubtedly, subsurface conditions had also undergone some changes during this interim. Nevertheless, reasonable confidence is placed in the accuracy of the topography and subsurface measurements.

The tests for soil properties in the Zena Creek study area have previously been described, and their results discussed. Admittedly, there are questions about the accuracy of the measured soil properties. The reader is cautioned not to extrapolate, or place excess confidence in these results for purposes of decisionmaking in other regions of the Idaho Batholith. Nor should any of these results be considered absolutely correct within the Zena Creek study area. Often in studies of this type, there is a strong tendency to question the method of analysis when discrepancies between the "prototype" and "model" are discovered. However, it must always be remembered that the assumed strength properties have been determined under laboratory conditions which never perfectly duplicate the actual field conditions. Further, it must be realized that the field conditions are continually changing due to geologic and climatic variations, and thus the soil properties are also continually changing. Therefore, it will be noted that the analyses have been conducted to account for variations in the soil properties.

External loads were not considered in the analyses because of poor definition. However, it is believed that the "rain on snow" so often referred to by many observers constituted a significant load on the road fills and denuded slopes. Most references to this condition emphasize the soil saturation aspects and neglect the importance of its weight.

One other factor, which is discussed briefly in the conclusions of the analyses, is the effect of sonic booms. There is a strong suspicion that these shock sources might also have played an important role as external loads leading to failure.

The description of seepage conditions in this region is undoubtedly the most questionable and complex factor detracting from the reliability of the analyses. There

is no doubt that better and more rigorous assumptions regarding the subsurface flow might have been made, or that more exact and detailed field tests might have been conducted to improve the reliability of the analyses. However, neither time nor funds would permit these desirable refinements, nor were such refinements necessary to demonstrate the probability and predictability of the occurrences of failure in the Zena Creek study area. The matter of ground water flow characteristics in the Idaho Batholith is deserving of perhaps the greatest immediate research endeavor if development of this region is to be continued and accelerated.

Finally, the reliability or exactness depends upon the correctness of the analysis procedures. All of the techniques used in this investigation are widely used and accepted. However, as mentioned in connection with soil properties and seepage conditions, many assumptions and idealizations are made which, to greater or lesser degrees, depart from the actual field behavior. It is important to know whether these assumptions are made for convenience (ease of computation) or out of ignorance; but this knowledge is not nearly so important as the fact that these assumptions are made and that, therefore, another source of error must be recognized. It is beyond the scope of this report to elaborate upon this matter except to note that, in general, the safety factors obtained by the ordinary method of slices are conservative. That is, for design purposes, this method usually will yield a lower computed safety factor than will most other more refined methods. More important, the actual factor of safety will usually be higher than the computed factor. Therefore, in analyses of the type performed in this study, a computed safety factor less than 1.0 may, or may not, mean that failure actually would occur.

It must also be understood that the methods used in these analyses are based upon the assumption that the soil mass behaves, or moves, as one or more discrete, solid units. In fact, most soils behave plastically. Further, it is strongly suspected that the dominant mode of failure in most of the cases discussed was liquefaction, wherein the soil mass behaves neither elastically nor plastically, but rather as a heavy fluid. No analytic techniques are yet available for completely describing this phenomenon, although the conditions leading to liquefaction are reasonably well understood and avoidable.

Before proceeding with the analyses, it is appropriate to briefly discuss the typical subsurface conditions found in the study area and, in particular, the assumptions regarding ground water conditions. A typical subsurface profile in the natural, undisturbed state, is shown in figure 10.

Referring to figure 10, the major portion of the flow that affects the stability of slopes occurs above the competent rock, although this deeper bedrock is also weathered and fractured and undoubtedly conducts considerable flow. What is referred to as the weathered zone is actually a transition zone composed of highly fractured, weathered material near its top and increasing in content, angularity, and size of stones, and also in unit weight, from the top to the bottom of the layer. The topsoil is almost without stones. Under certain climatic conditions and during certain times of the year, it is probable that all of the subsurface materials are saturated, with the top flow line coincident with the ground surface. This seepage condition would be the most critical in, and was assumed in the analysis of, natural slopes.

When the natural slope is interrupted by a road prism, the subsurface profile appears typically as shown in figure 11. In this situation, part or all of the relevant flow is interrupted. Above the cut slope, under the most critical conditions, the top flow line is distorted as shown in figure 11. This distortion, or drawdown, is not so critical as would be the case if the top flow line could be maintained coincident with the surface of the slope. Hence, in analyses of the cut slopes, a conservative assumption that no drawdown occurs was used.

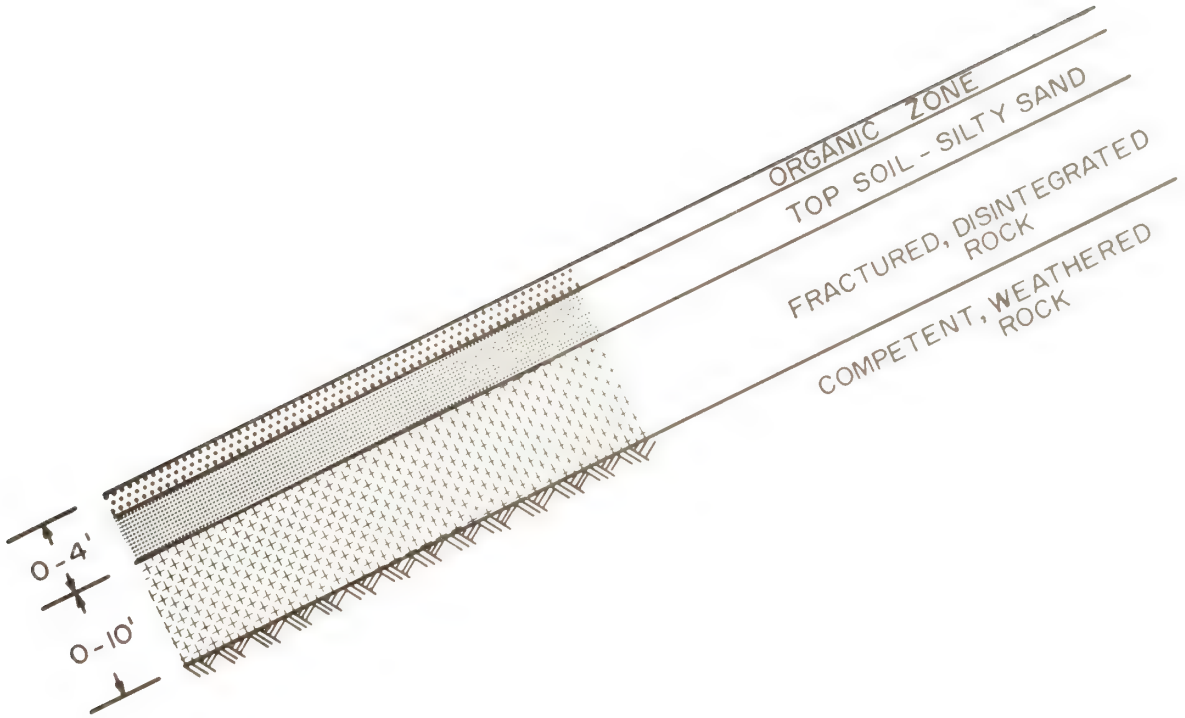


Figure 10.--Typical soil profile.

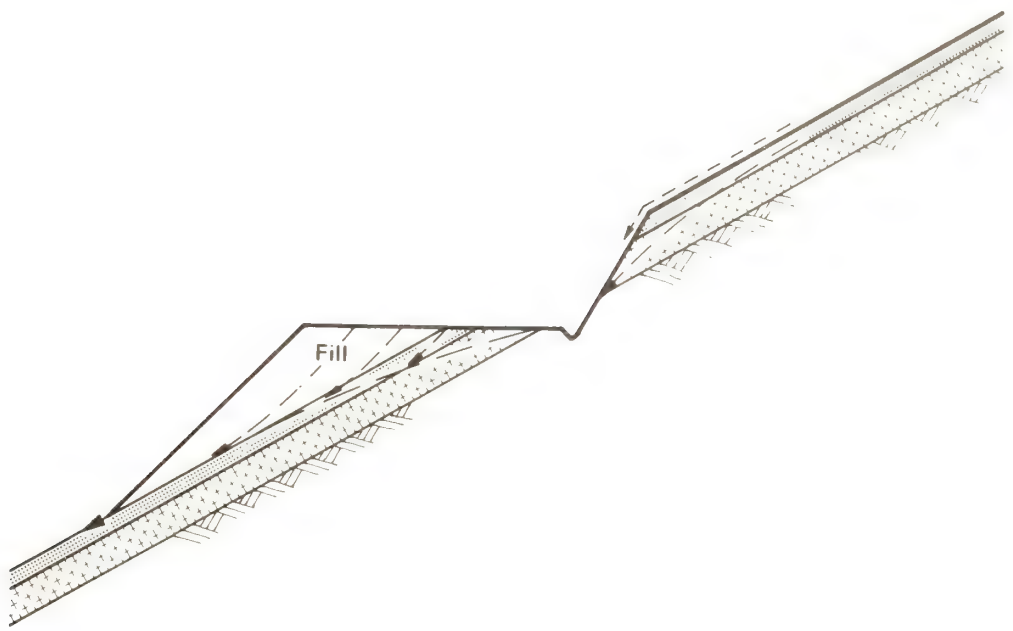


Figure 11.--Post construction profile and flow conditions.

Of course, overland flow may be occurring simultaneously, as shown in figure 11, some of which is caused to seep vertically downward to reach the phreatic surface.

Below the road surface, the top flow line probably appears as shown in the fill section of figure 11. Represented is an equilibrium situation, wherein the ditch is full of water. Water on the road surface and fill slope tends to seep vertically downward to reach the flowing ground water.

Situations can arise, however, where water accumulates in the road surface. In such cases, active seepage throughout the section, with flow roughly parallel to the fill slope, is possible. It is this extreme situation which was assumed in the analysis of fill-slope failures.

Where an embankment or through fill crosses a draw, the situation can be represented as shown in figure 12. The culvert installation may interrupt part of the subsurface flow, thus causing some drawdown of the top flow line above the embankment. Below the culvert inlet, subsurface flow continues, and at some location downslope may again coincide with the ground surface. It is possible for the top flow line to rise above the original ground surface and into the fill material immediately downslope from the culvert inlet. Thus, a conservative assumption in such a case would be one in which the embankment was considered as an earth dam; furthermore, this "dam" would have a free water surface upslope at the elevation of the culvert entrance, and tailwater elevation at the toe of the downstream slope.

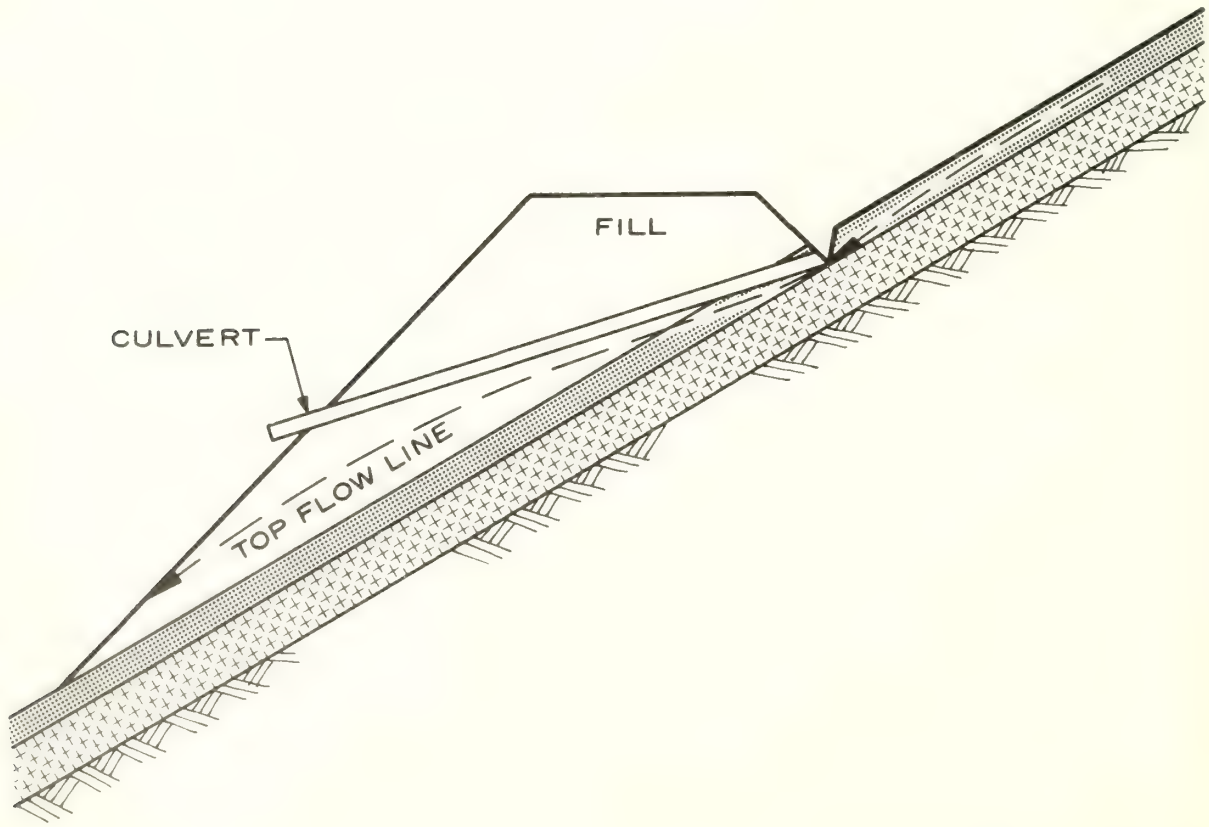


Figure 12.--Subsurface flow conditions for through fills.

GONSIOR M. J. and GARDNER R. B.

1971. Investigation of slope failures in the Idaho Batholith, USDA Forest Serv. Res. Pap. INT-97, 34 p., illus.

An investigation of slope failures in the Zena Creek sale area on the Payette National Forest is described. Conventional methods of field and laboratory testing were applied to describe soil properties. Stability analyses were conducted to demonstrate the predictability of failures. Recommendations for future construction in similar terrain are made.

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Figure 13.--This illustrates proximity of site 917-1 to ridgetop.

Site 917-1. As shown in figures 13 and 14, this site is a stable embankment crossing a small gully on Road 917 and is located approximately 1.7 miles from the junction of Road 917 and the main Secesh Road (fig. 4). A plan view and three profiles are shown in figure 15.

Provisions for surface drainage seem to be adequate at this site. A culvert has been properly installed in the embankment with a suitable downspout and wire mesh catchment to dissipate the hydraulic energy. The close proximity of the site to a ridgetop can be seen in figure 13, illustrating the relatively small drainage area contributing to the culvert flow. The road has a 9 percent favorable grade at this location and a similar embankment with drainage equally well provided for is located only about 100 yards up the road (east) from this site. Therefore, surface water flowing down the road does not present a drainage problem at site 917-1. A soil-cement berm, which can be seen in figure 14, prevents road-surface water from eroding the outside slope of the embankment.

Figure 14.--This illustrates berm and culvert downspouts for proper handling of water at site 917-1.

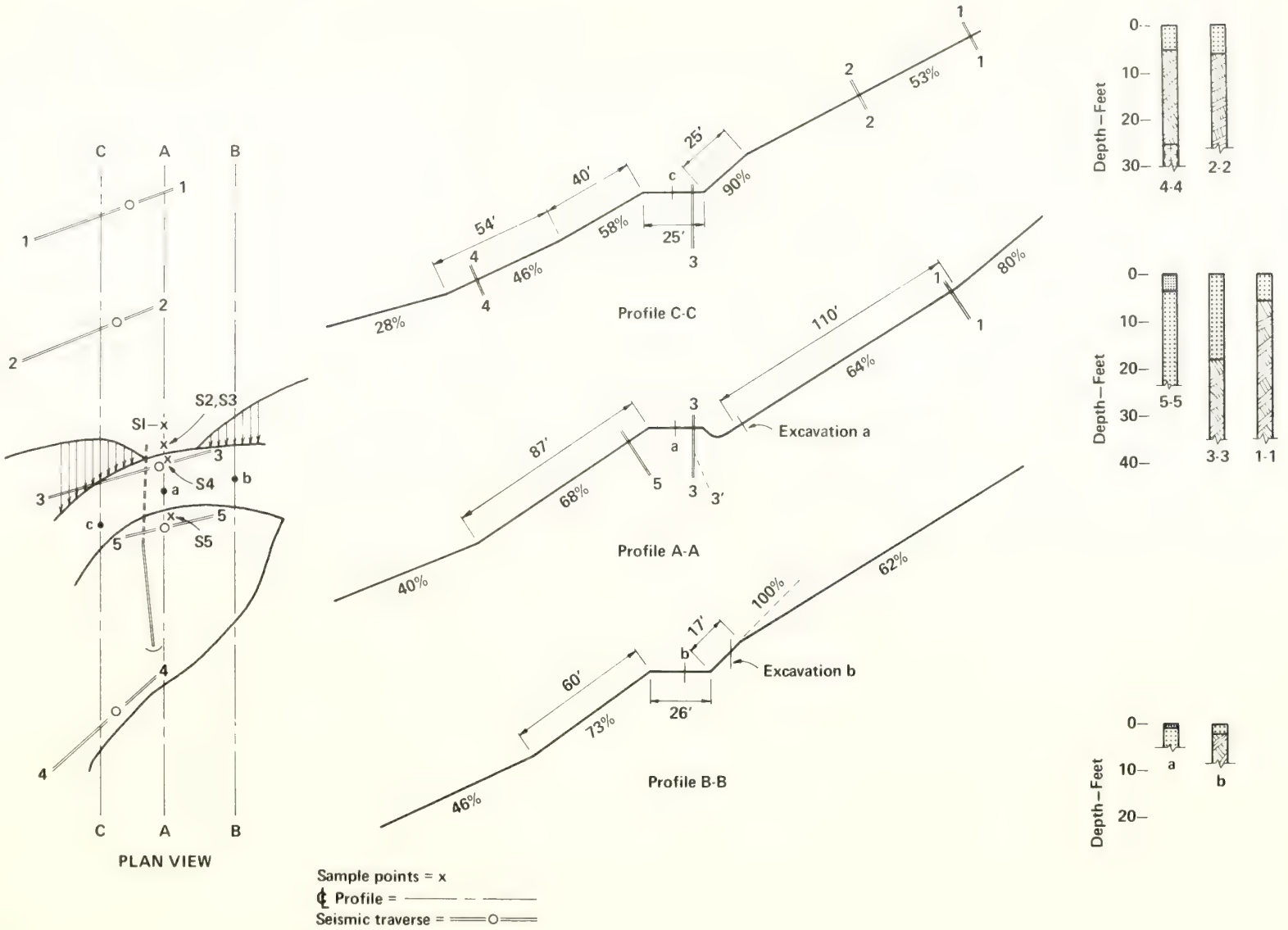


Figure 15.--Description of test site 917-1.

Five seismic traverses were run at site 917-1; the approximate locations are shown in figure 15. The small circles on the double lines represent the approximate locations at which the seismic interpretations are valid. Following are the interpretations, with the accompanying seismic velocities included:

Traverse 1: 5.5 feet of loose material, velocity = 1,050 feet per second (f.p.s.) overlying fractured rock (3,125 f.p.s.) which extends at least to an additional 30-foot depth.

Traverse 2: 6.2 feet of loose material (850 f.p.s.) overlying fractured rock (2,350 f.p.s.) which extends at least to an additional 20-foot depth.

Traverse 3: 5 feet of fill material (900 f.p.s.) overlying 13.2 feet of loose material (900 f.p.s.), beneath which is fractured rock (4,500 f.p.s.).

Traverse 4: 5.15 feet of loose material (540 f.p.s.) overlying a 20-foot thick layer of fractured rock (2,330 f.p.s.), beneath which is sound rock (20,000 f.p.s.).

Traverse 5: 3.5 feet of very loose material (540 f.p.s.) overlying at least 20 feet of denser material (1,100 f.p.s.).

Also shown in figure 15 are the approximate test pit locations.

Lines A-A, B-B, and C-C in the figure are the locations of the profiles sketched adjacent to the plan view in figure 15.

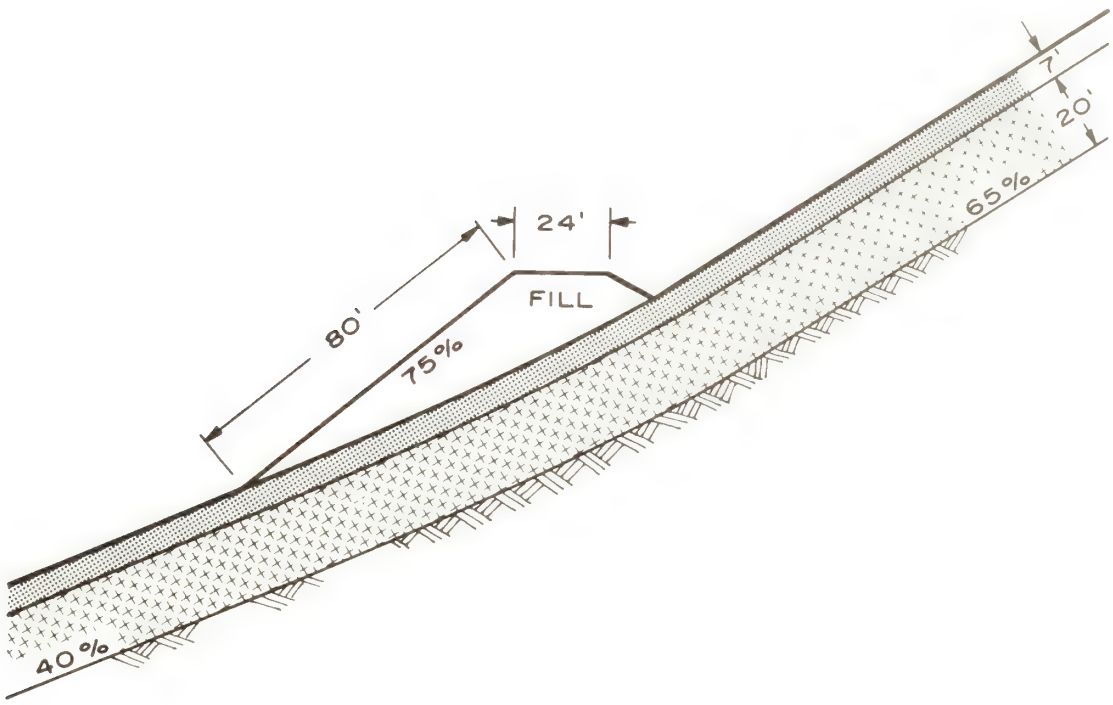


Figure 16.--Representative profile, site 917-1.

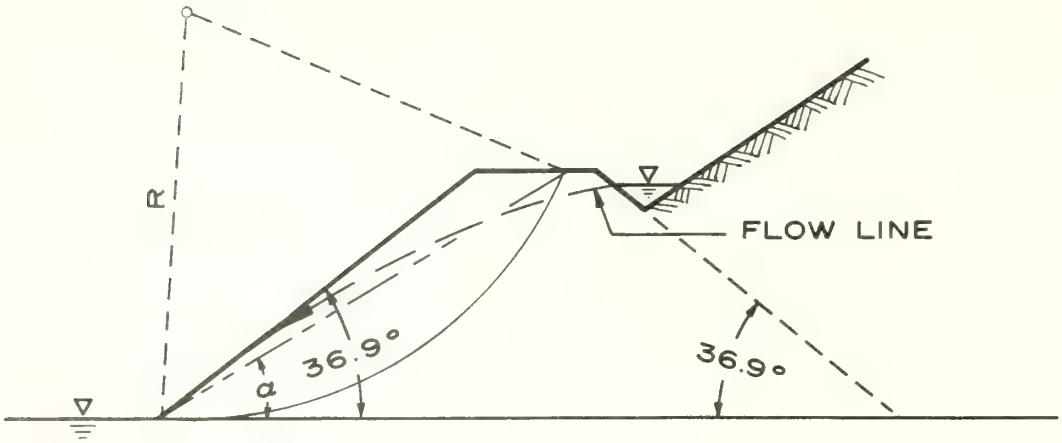


Figure 17.--Assumed conditions for L. Casagrande solution at site 917-1.

Site 917-1 was included in the investigation primarily for its comparative value and also to serve as a check on the stability analysis techniques and measured soil-strength parameters. Because a safety factor of unity separates stability from instability, theoretically no hypothetical failure surface with a safety factor less than 1.0 should exist in this embankment.

Based upon the data available, a representative profile of this site is shown in figure 16.

For an initial analysis, an in-place dry unit weight of 115 pounds per cubic foot (p.c.f.) is assumed (noting from table 2 that the dry unit weights found at sampling sites 917-1-4 and 917-1-5 were 119 p.c.f. and 106.3 p.c.f., respectively). The corresponding void ratio, e, would be 0.44, and saturated unit weight, γ_t, would be 134 p.c.f.

A conservative analysis can be performed by assuming a plugged culvert and subsurface flow as shown in figure 12. In this analysis, the L. Casagrande solution for the top flow line through a triangular dam is used[2] (see Taylor, p. 181). It is arbitrarily assumed that the upstream and downstream slopes of the dam are equal. Figure 17 depicts the assumed cross section.

A series of analyses were conducted, assuming circular failure arcs and using the method of slices. In all cases, failure arcs were assumed to pass through the toe of the fill slope. The material above the top flow line was assumed to weigh the same as that below the top flow line, or 134 p.c.f. The results of these analyses, assuming that $c = 0$ and $\phi = 35°$, are shown in figure 18 and, alternatively, in figure 19, wherein the parameters R and α are as shown in figure 17. Safety factors significantly lower than 1.0 are noted in figures 18 and 19. Three major conclusions can be drawn from these analyses:

(1) The assumed friction angle of 35° may be too low.

(2) The material actually possesses a minimum cohesive strength, even when saturated.

(3) The assumed seepage conditions are significantly more severe than would ever arise naturally.

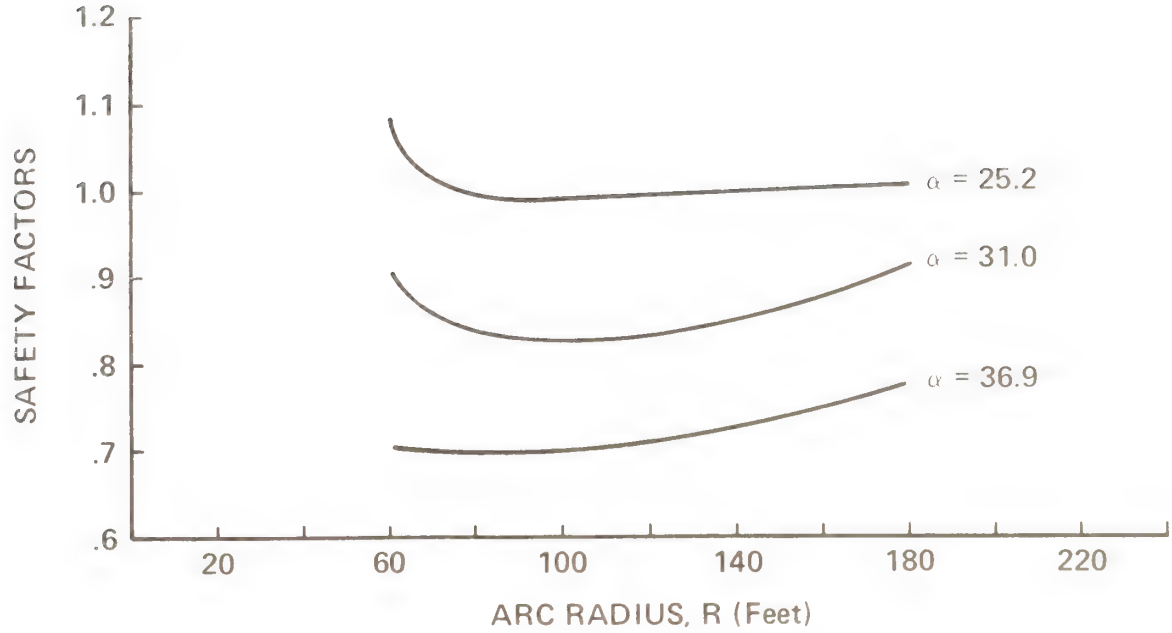


Figure 18.--Safety factors vs. arc radius, R, for conditions given in figure 17.

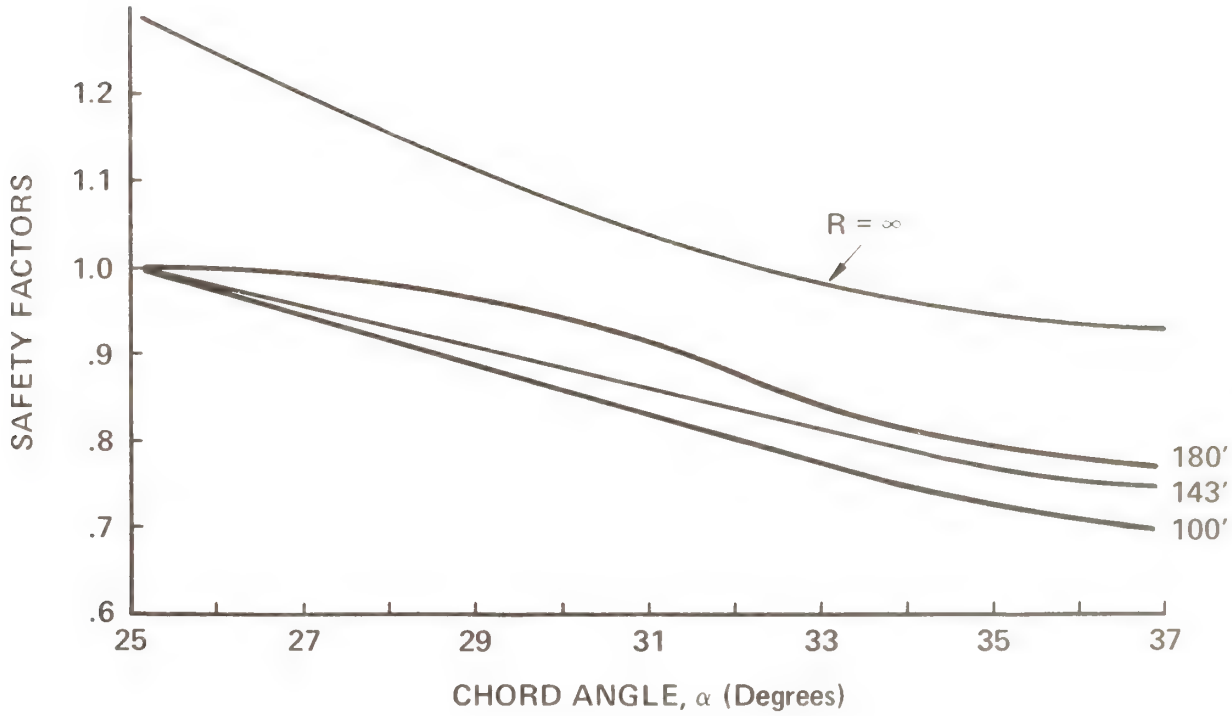


Figure 19.--Safety factors vs. arc chord angle, α, for conditions given in figure 17.

Although the effective friction angle in the field may exceed 35°, it is believed that the angle stated in the first conclusion is a reasonable estimate based upon the consistency of the laboratory results. Further, where the safety factors are as low as 0.7, a friction angle of 45° would be necessary in the absence of cohesion to increase the safety factor to 1.0. It seems inconceivable that the estimate of the friction angle would be this much in error.

With regard to the second conclusion, it seems possible that this material may possess sufficient cohesive strength, even when saturated, to assure stability at this site. The computed maximum cohesion required for a safety factor of 1.0, among all of the trial failure arcs, was only 175 pounds per square foot (p.s.f.), or about 1.2 pounds per square inch (p.s.i.), assuming $\phi = 35°$. Thus, although it has been concluded that no cohesive strength should be used for design purposes, it must be recalled that even in the saturated triaxial tests on loose material, a cohesive strength of 1 p.s.i. was estimated. Obviously, therefore, some moderate cohesion, combined with a slightly greater estimate for the friction angle, would assure computed safety factors in excess of 1.0 for all the trial failure arcs in this analysis.

The third conclusion is undoubtedly correct. There is no evidence that the culvert has ever become plugged at site 917-1. Even in the event of such an occurrence, it is doubtful that a stable seepage condition as severe as that assumed in these analyses would arise. However, since the exact flow pattern cannot be predicted, a series of analyses were conducted assuming no seepage. This was done in order to establish a minimum upper limit for the safety factors at this site. The results of these analyses are shown in figure 20, where the parameters R and α are as defined in figure 17.

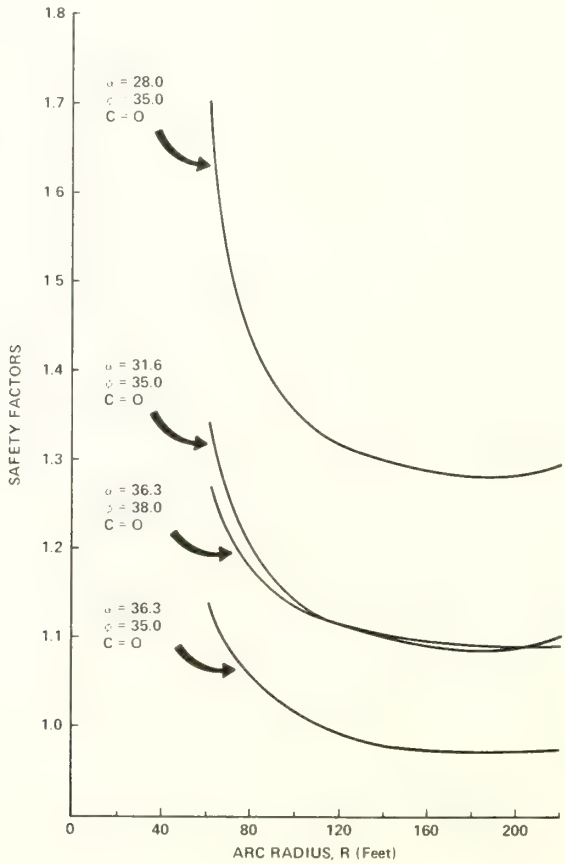


Figure 20.--Safety factors vs. arc radius, R, without seepage for site 917-1.

Again, it is noted that either the friction angle (ϕ) or cohesion (c) has been underestimated, since safety factors less than 1.0 were calculated. In these analyses, an estimated cohesive strength of 1.0 p.s.i., or 144 p.s.f., would have resulted in a minimum computed safety factor of approximately 1.4.

To evaluate the influence of error in the estimate of ϕ, a series of analyses, again assuming no seepage, were conducted with $\phi = 38°$, $c = 0$, and $\alpha = 36.3°$. The resulting safety factors are shown in figure 20. Thus, only moderate increases in either ϕ or c, or in both ϕ and c, result in computed safety factors indicating stability.

Finally, an extreme seepage condition wherein the top flow line is coincident with the fill slope was analyzed by assuming the validity of the infinite slope stability theory. Ordinarily, an arbitrary requirement that the length of failure be in excess of 20 times its depth is made. Noting that the fill slope is 80 feet long, a depth to failure of 4 feet is assumed. From the relationship:

$$c_d = \gamma_t H \cos^2 i \left(\tan i - \frac{\gamma_b}{\gamma_t} \tan \phi_d\right),$$

where

γ_t = saturated, or total, unit weight

H = vertical depth to failure surface

i = ground slope

γ_b = buoyant unit weight

ϕ_d = friction angle

and letting

γ_t = 134 p.c.f., i = 36.9°, ϕ_d = 35°, H = 4'

γ_b = 71.6 p.c.f.

we compute a developed cohesion of 129.3 p.s.f., or

c_d = 0.9 p.s.i.

Figure 21.--Evidence of incipient failure at site 917-3, cracking and settlement of fill.

Figure 22.--Additional evidence of incipient failure, site 917-3 (test pit excavation shown in top of photo).

Of course, this is the most extreme seepage condition imaginable for this site, but the computed required cohesion is compatible with the laboratory strength test results.

Thus, although the assumption that these soils are cohesionless is conservative and appears desirable for design purposes, it may be necessary to recognize some minimum cohesion in the remainder of the site analyses. It may also be necessary to perform the analyses assuming various values for ϕ.

Site 917-3. This site, shown in figures 21-23, is located on Road 917 approximately 4.2 miles from the junction of Road 917 and the main Secesh Road (fig. 4). Considerable importance is placed upon the analysis of this site, primarily because failure is impending, as evidenced by cracking in the road surface and settlement of the outside portion of part of the fill (figs. 21 and 22). In addition, a narrow portion of the fill has failed, as shown in figure 23. Thus, this site offered the best opportunity for material sampling and definition of the mode and shape of failure.

Figure 23.--Narrow failure on fill at site 917-3.

Plan view and profile sketches appear in figure 24, along with pertinent seismic profile and test pit information.

Following are the seismic interpretations for site 917-3:

Traverse 1: 21.5 feet of loose material (1,150 f.p.s.) overlying at least 40 feet of fractured rock (3,000 f.p.s.).

Traverse 2: 4.8 feet of very loose material (830 f.p.s.) overlying at least 25 feet of fractured rock (2,500 f.p.s.).

Traverse 3: 3.1 feet of very loose material (770 f.p.s.) overlying at least 20 feet of loose material (1,100 f.p.s.).

A berm, although apparently not of soil cement, is located along the outside edge of the road surface, as at site 917-1. However, the road has negligible grade through this section, and the berm apparently acts as a small dam. This causes water to collect on the road. In fact, there may even be a slight dip in the longitudinal axis of the road, as evidenced by the fact that water had been flowing along the cracks and into the failed section from both directions.

Apparently the incipient failure surfaces, as is the scar left by the narrow failure, are at relatively shallow depths below the fill slope. Ignoring for the moment any water infiltrating from the road surface, the ground water conditions represented by figure 11 would seem to have minimal influence in the outer portion of the fill where failure occurred and is impending. To evaluate the accuracy of the laboratory estimates for ϕ and c, a series of analyses were conducted assuming circular failure arcs, with an assumed saturated unit weight of 125 p.c.f., but without excess boundary neutral stresses along the failure arc. (From table 2, test pits 917-3-1 and 917-3-3, an average dry unit weight of 100 p.c.f. and e = 0.66 provides for a saturated unit weight of 125 p.c.f.). The analyses were made under the condition that all failure arcs passed through the toe of the fill slope, where the fill slope was 70 feet in length and at a slope of 38.6° (profile A-A).

The results of these analyses are shown in figure 25, wherein R and α are again defined as in figure 17.

Under the assumption that $\phi = 35°$ and c = 0, several trial failure arcs were found with a safety factor less than 1.0. As discussed in connection with site 917-1, it is possible that this material retains some cohesive strength, even under the condition of saturation with seepage. Noting that the lowest safety factors were obtained when $\alpha = 38.6°$, a series of analyses were conducted at this steepest chord angle when $\phi = 35°$ and c = 1 p.s.i. As seen in figure 25, the safety factors were significantly increased. However, these increases were more pronounced at a greater R value. Since the appearance of the failure indicates a failure arc of low curvature, i.e., of long radius, the safety factor vs. radius curve for $\phi = 35°$ and c = 1 p.s.i., in figure 25, does not seem to comply with the actual failure surface nearly as well as do the curves for $\phi = 35°$ and c = 0.

Finally, a series of analyses were conducted with ϕ increased to 38° and c = 0. The results of these analyses are also shown in figure 25, and seem to be most compatible with the observed conditions at the site.

The low depth-to-length ratio of the failure at this site suggests that the infinite slope stability theory might be applied. Assuming a depth no greater than one-twentieth the length, or about 3.5 feet, developed cohesion values of only 0.18 and 0.03 p.s.i. are necessary for stability in the absence of seepage forces, for $\phi = 35°$

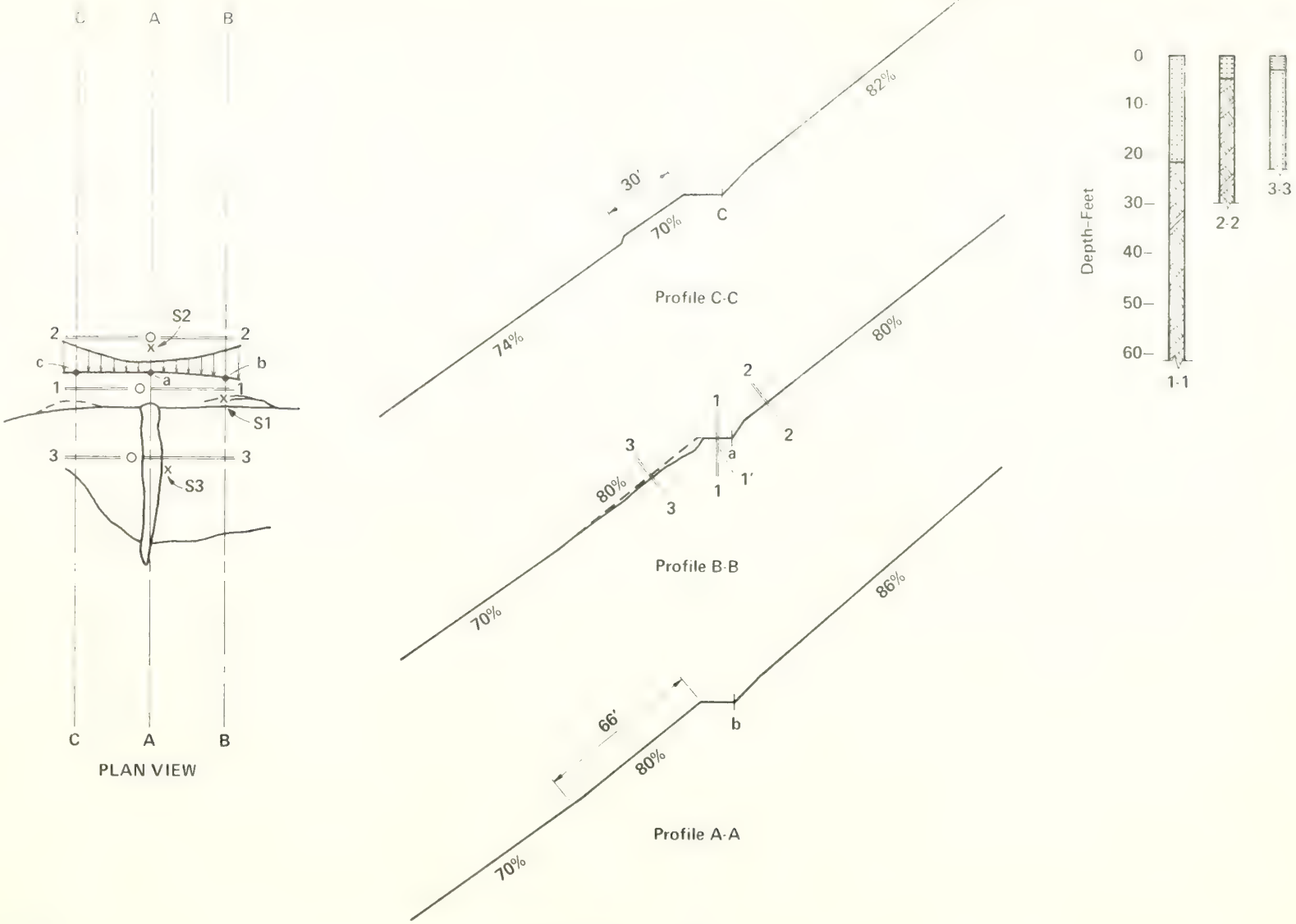
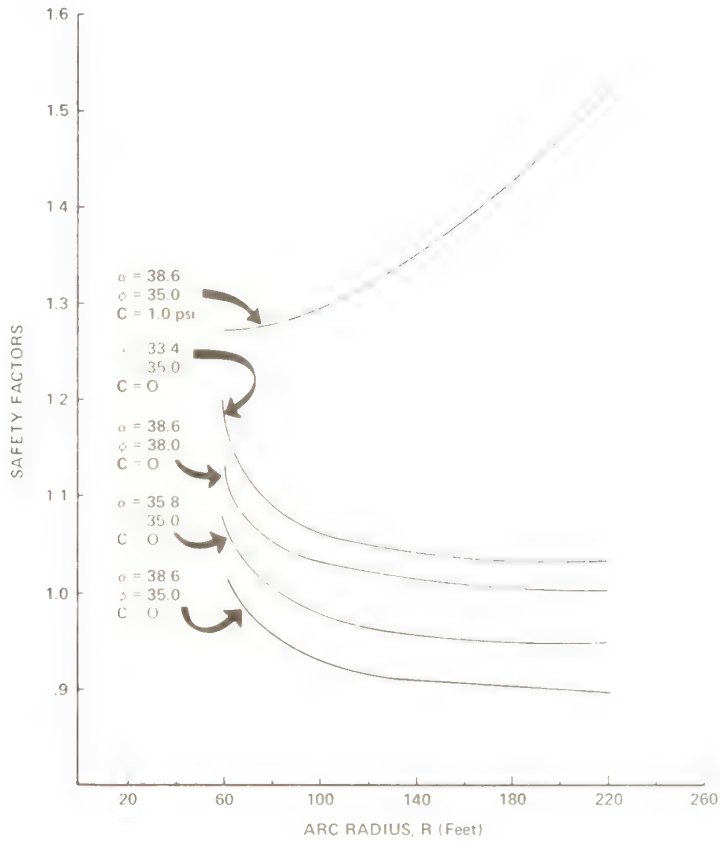


Figure 24.--Description of test site 917-3.

Figure 25.--Safety factors vs. arc radius, R, for site 917-3, with zero boundary neutral stresses.



and 38°, respectively. Under the extreme condition that would permit seepage throughout the fill, with a top flow line coincident with the fill slope, the necessary developed cohesion values would be 0.83 and 0.75 p.s.i. for ϕ = 35° and 38°, respectively. Such an extreme seepage condition seems unlikely at this site, although it has already been noted that water collected on the road at this location. It is possible, however, that water infiltrating from the road surface combined with the ground water, resulting in emergence of the water at some location above and near the toe of the fill slope. A subsequent "blow out," or quick condition might have occurred locally, and the resultant loss of support at the toe would have allowed the upslope material to slide.

In any case, the analyses of this site and of site 917-1 seem to indicate that a more realistic value for the friction angle in this material might be about 38°.

One additional factor should be noted in connection with site 917-3. Timber has been left standing at and below the toe of the fill slope. It is believed that these live trees and their fully developed root systems significantly enhance the stability of the site. Most certainly they were instrumental in preventing complete translation downslope of the material which partially failed.

Site 917H-3. This site is a relatively long, narrow failure of material lying in a swale above Road 917H at a location within 100 yards of site 917H-2. It is pictured in figures 26 and 27, as viewed from the bottom and top of the failure, respectively.

Figure 26.--View from below site 917H-3, illustrating its long, narrow, and shallow characteristics.

Plan view and profile sketches of the site are presented in figure 28. The seismic interpretation at traverse 1 is: 6.7 feet of loose material (1,140 f.p.s.) overlying at least 35 feet of solid rock (10,000 f.p.s.).

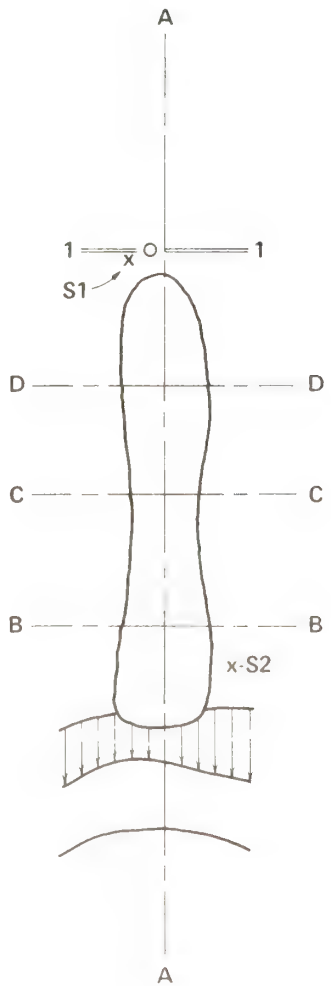
Although the road cut intersected the bottom of the swale, it is difficult to state with certainty that this resulted in sufficient loss of support to cause failure. By using appropriate techniques for the analysis of stability of a cohesive, infinite slope, it is apparent that the natural slope might have failed in the absence of road construction. Such an analysis follows:

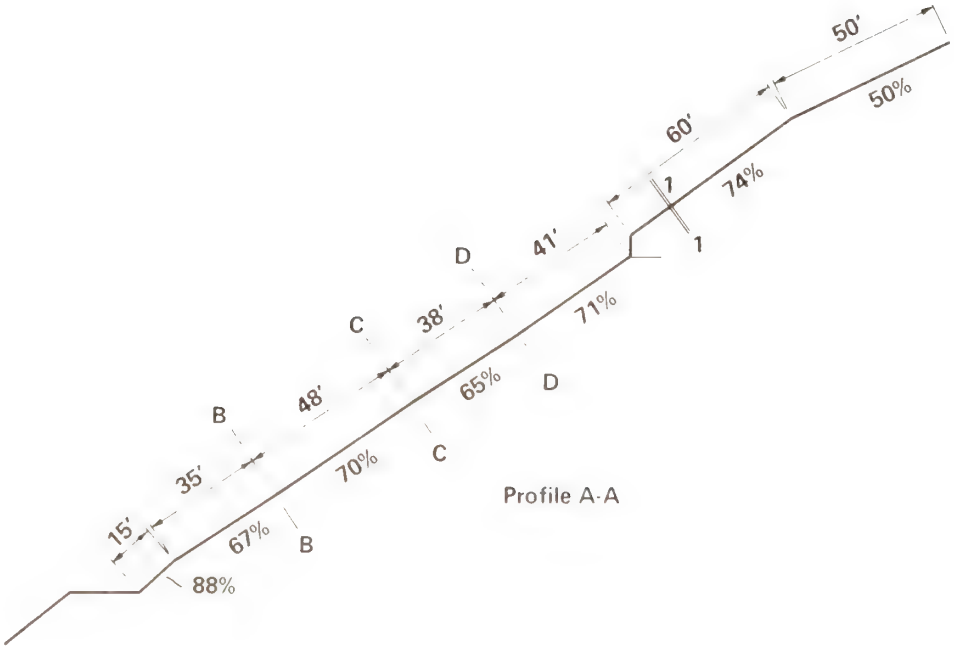
Assume a natural slope, i = 70 percent (35°), void ratio, e = 0.86 (γ_d = 89 p.c.f.), and average depth to failure surface, H = 5 feet. The appropriate relationship for the dry condition is:

$$\frac{c}{\gamma H} = \cos^2 i \ (\tan i - \tan \phi).$$

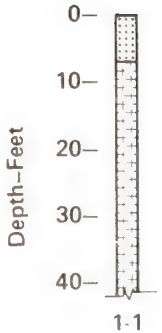
Since i = ϕ, no cohesion is required for stability in the dry condition.

Figure 27.--View from above site 917H-3, illustrating road at bottom.





Profile A-A



Profile B-B

Profile C-C

Profile D-D

Figure 4.--Location of test pits, 1978-3.

In the case of saturation, however, the appropriate relationship describing stability is:

$$\frac{c}{\gamma_t H} = \cos^2 i \ (\tan i - \frac{\gamma_b}{\gamma_t} \tan \phi).$$

where now $\gamma_t \cong 118$ p.c.f. and $\gamma_b \cong 55$ p.c.f. Assuming $\phi = 35°$, a cohesive strength of

$$c = \gamma_t H \cos^2 i \ (\tan i - \frac{\gamma_b}{\gamma_t} \tan \phi) = 148 \text{ p.s.f.}$$

$$\cong 1.0 \text{ p.s.i.}$$

is required for stability. Even if $\phi = 38°$, a cohesive strength of 133 p.s.f., or approximately 0.9 p.s.i., would be needed. It is reasonable, therefore, to assume that failure might have occurred without road construction.

An additional factor to consider is that all timber had been removed from site 917H-3. Yet, adjacent to this site is equally steep terrain also intersected by the road cut, but this terrain has not been denuded and remains stable. There is evidence throughout the Zena Creek and adjacent watersheds that timber harvesting on steep slopes, with subsequent destruction of the stabilizing effects of live root systems, may contribute to the occurrence of shallow landslides.

Finally, as mentioned above, this slide occurred in a moderate natural swale. The existence of the swale indicates some form of structural weakness in the subsurface, which ultimately might have led to deeper dissection. Thus, the failure at this site, though undoubtedly hastened by construction and timber harvesting activities, might easily be considered to be merely one of a series of inevitable geomorphic events leading to a deeper gully.

Conclusions From Failure Investigations

For the failures investigated, it must be emphasized that no single cause can be isolated. Indeed, each individual failure was probably a result of a combination of circumstances.

Perhaps the natural instability of the terrain in the Zena Creek and similar drainages is of greatest importance. In the absence of human activities, a climatic event such as that which occurred in 1965 could be expected to result in landslides even on undisturbed terrain, though the frequency of such occurrences is undoubtedly increased manyfold as a result of road construction and timber harvesting operations. The bedrock and soils are extremely frangible, and landslides are undoubtedly very important as landforming processes in this region. Thus, it should be recognized that soil is continuously undergoing displacement in the relatively rapid natural dissection of the terrain. This recognition, however, should not provide rationalization for the accelerated soil movement resulting from human exploitation. Instead, it should supply an impetus for considerably greater care in the use of these lands.

In every road-associated failure, slope steepness was an important factor contributing to instability. As a consequence of the laboratory tests, it appears that no unretained slopes should be allowed in excess of 35°, or 70 percent, on road fills. Although both natural and artificial slopes in excess of 35° can be found in many locations, it is believed that most of the necessary additional strength required to maintain these slopes is from more or less temporary sources. For example, live tree roots extending into the deeper fractured zones undoubtedly provide some structural reinforcement to the upper soil layers. Also, large fragmentary boulders embedded in newly

placed fills provide an interlocking and keying effect that permits creation of steeper slopes. However, the rapid disintegration of the larger stones, and the death and rotting of tree roots can result in significant stability reductions.

Aside from mass stability requirements, erosion of finer particles from the surface of steep slopes is considerably enhanced when the slopes are at, or near, the angle of internal friction. Further, since revegetation of these slopes appears to be a difficult and slow process, such steep slopes are serious contributors of sediment for extended periods.

Water was another important factor contributing to instability. As demonstrated in several of the stability analyses, complete saturation with equipotential lines assumed normal to the ground surface results in appreciable reductions of safety factors. Although seepage conditions are probably never quite so severe as assumed for some of these analyses, neither are the safety factors in the assumed dry conditions sufficiently large to compensate for even moderately adverse water conditions. Furthermore, there is good evidence that with the passage of time after construction and considering the weathering and compaction, the seepage conditions may worsen from the standpoint of stability. Undoubtedly many of the road-associated failures could have been prevented if surface water had been better handled.

Minimal compactive effort in the road fills was evidenced by the low in-place densities. The problem of liquefaction, a result of high void ratios in combination with saturation, or near saturation, in these soils is apparent throughout the Zena Creek area. There is little doubt that liquefaction occurred at practically every large failure, as evidenced by the long transport distances (often several hundred yards) and "mud" splattered on tree trunks up to heights of several feet. This is not just a problem in the road fills, however, as the in-place densities at shallow depths in the natural materials were equally low. Nevertheless, even nominal compaction of the fills during construction should have prevented some failures, and certainly should have reduced both the size of some of the failures and the ease of transport to the streams.

Aside from the liquefaction problem, significantly lower strain energy is required for failure in these loose, uncompacted materials. In denser materials, shear strain must be accompanied by a corresponding volumetric increase. But in loose materials, either at or above the critical void ratio, shearing can occur without volume change, and volume decreases usually accompany failure. Thus, lack of compaction considerably increases the chances for failure even in the dry condition.

Besides the apparent lack of compaction control, other examples of poor construction practices were in evidence in the Zena Creek road system. At one site, a large log was found embedded in the fill. The inclusions of logs and stumps in embankments and fills should never be permitted. Loose surface materials should be compacted and keyed if clean, or removed if not. It is doubtful that adequate clearing and grubbing were performed in most locations.

Cyclic displacement resulting from sonic booms is another factor which may be of significance, but one for which very little information is presently available. During the field investigation the authors experienced several unnerving shocks caused by the supersonic aircraft that passed over the study area, usually two or three times each day. It is suspected that these shocks may provide sufficient ground motion to initiate liquefaction in some of the more critical slopes. The authors believe that this deserves some additional study; however, they do not believe that sonic booms would be of much consequence to the behavior of adequately designed and compacted slopes.

Finally, as discussed in connection with sites 917-3 and 917H-3, live trees probably are important factors influencing the stability of both natural slopes and road fills. It is suspected that the live tree root systems exert a significant stabilizing

influence due to both mechanical reinforcement and moisture depletion. To avoid future distress, all stumps and large roots should be removed before placing road fills. It is believed, however, that barriers of live trees should remain undisturbed immediately below the toe of the fill slope and above the cut slope. In addition, it is suspected that weathering of the subsurface materials may be accelerated after removing the timber since daily temperature extremes are undoubtedly more severe after timber harvest. Thus, it is not sufficient to consider only surface disturbances in the planning of harvesting operations but, in addition, long range mass stability must also be an important consideration.

Summary and Recommendations

An investigation of several slope failures in the Zena Creek watershed, located in the Idaho Batholith, successfully explained the causes of failure and provided an opportunity for a more critical evaluation of current road construction and harvesting practices.

A natural instability exists in the terrain at Zena Creek and in similar drainages. In the absence of human activities, a climatic event such as occurred in 1965 could be expected to result in landslides even on undisturbed terrain, though the frequency of such occurrences is increased manyfold as a result of certain harvesting and road construction practices. It is this accelerated damage that must be greatly minimized.

In every road-associated failure, the steepness of both natural ground slope and fill slope was an important factor contributing to failure. As a result of the laboratory tests and subsequent stability analyses, it can be concluded that no man-made slopes exceeding 35° should be constructed without special provisions to assure stability.

Aside from the mass stability problems, erosion of finer particles from surface slopes is considerably enhanced for cohesionless materials when slopes are at or near the angle of internal friction.

The problems of liquefaction, a result of high void ratios in combination with saturation, were common. The long transport distances of failed fill materials and the presence of "mud" splashed high on tree trunks were irrefutable evidence that liquefaction had occurred in conjunction with most failures. High void ratios were not just a problem found in road fills, but were common at shallow depths in natural material. Nevertheless, even nominal compaction of the fills could have prevented some of the failures.

In addition to the low in-place densities and inadequate control of surface and subsurface flows, the presence of logs and other debris in the fills may have contributed to many of the road failures.

Live roots and trees are probably important factors influencing the stability of natural and artificial slopes. In addition, it is suspected that disintegration of the subsurface materials may be accelerated by exposure to greater daily temperature extremes as a result of timber harvesting.

The type of investigation conducted and reported upon herein probably cannot be adopted as a routine procedure for all situations. Certainly one may find stable natural and man-made slopes in the Zena Creek and similar drainages which are greater than 70 percent. Similarly, failures of slopes less than 70 percent are possible. It should be understood that the tests and analyses conducted in this type of investigation are based upon extremely simplified models and assumptions of uniformity and homogeneity.

Where engineers are called upon to design and analyze man-made earth structures, and where such structures can be constructed to closely approximate the models of analysis, then the methods of analysis employed can be considered reasonably reliable. However, when dealing with the vagaries of nature or with complex and uncontrolled man-made structures, the confidence one places in most methods of investigation and analysis must necessarily be reduced.

It is important, however, that some measure of soil strengths and depths, and their degree of variability within an area for which development is planned, be obtained before development proceeds. Such parameters may be determined by intensive exploratory and laboratory techniques, by correlations between topography and movement, or simply through experience gained in other similar areas; but without this knowledge the location and design of roads cannot proceed on a completely rational basis.

Similarly, knowledge of surface and subsurface water conditions must precede road location and design if erosion and landslides are to be avoided or controlled. Beyond these areas of information, the designers must exercise their professional judgments regarding the appropriate specifications, methods of analysis, and intensity of inspection and control during construction.

As a consequence of this investigation, the following tentative criteria are recommended:

1. Fill slopes should be specified by the design engineer and based upon suitable stability analyses. In no cases should unretained fill slopes exceed 70 percent.

2. Cut-bank slopes should generally be as steep as possible consistent with subsurface conditions. Slope rounding should be practiced when overburden depths require it.

3. In general, alignment should be sacrificed whenever possible to avoid deep fills and/or cuts.

4. All fill slopes should be compacted to a degree consistent with design standards and material properties.

5. Drainage facilities should be provided to prevent damaging concentrations of surface runoff and to avoid high pore pressures in cuts and fills.

6. All fill sections should be insloped with an adequate berm on the outside, unless adequate means for protecting the fill slopes against erosion can be provided. Benched sections can be outsloped providing adequate vegetative cover or other erosion protection remains after construction.

7. Specifications requiring log and debris removal from fill slope sections must be rigidly enforced.

8. All fill surfaces should be revegetated with suitable species as soon as possible after construction. In addition, rip-rap or other suitable debris should be placed at or near the toes of fill slopes to halt the downhill movement of sediment from the fill surfaces.

9. Roadbeds should be stabilized to prevent erosion and rapid deterioration.

10. Provisions should be made to prevent raveled cut-slope materials from reaching live streams.

Note that these recommendations merely constitute improvements, not complete solutions, and merely reflect engineering considerations pertaining to the management and use of this and other similar areas. Future knowledge about the behavior of these materials and the flow characteristics of surface and subsurface waters may require alterations of and additions to these recommendations.

Beyond these criteria, there are a great number of other environmental responses which must be understood; and knowledge of these responses must be applied if these lands are to be wisely managed. In addition, there appears to be a need for a subtle philosophical change in the traditional engineering approach to problem solving and design. Usually, the integrity of a road, dam, or any other structure is viewed as the primary goal, and thus natural processes such as erosion, seepage, and settlement are considered as impositions on the structure which must be controlled or withstood. Instead, the road or structure might better be viewed as an imposition upon the various natural processes, and location and design might better be oriented toward assuring the continuity of, or at least compensation for changes in, these natural processes. By so reorienting design philosophy not only should the integrity of roads and structures be better guaranteed, but the chances for causing undesirable changes in the functioning of natural systems should be considerably reduced. Of course, by changing the question from "What are the natural processes which will endanger the road's integrity?" to "How will the road influence natural processes?" the designer is forced to consider a broader spectrum of environmental factors. Thus, multidisciplinary cooperation and teamwork become not only desirable, but absolutely essential to the completion of the planners' and designers' work.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

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USDA FOREST SERVICE
RESEARCH PAPER INT-98
1971

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ABSTRACT

Clearcutting of lodgepole pine stimulates production of understory vegetation that may provide a grazing resource for livestock and big game for an estimated 20 years or more. Peak production of 800 to 1,000 lbs./acre occurred about 11 years after clearcutting. Prediction equations were developed to permit gross estimates of potential production and its change with time. Although palatability of the indigenous understory vegetation is low, the large acreages of lodgepole pine that are harvested annually warrant efforts to improve the quantity and quality of forage by reseeding.

Introduction

Lodgepole pine (*Pinus contorta* Dougl.) occupies 5.4 million acres in Montana (Wilson and Spencer 1967). This vast resource received limited commercial use until the early 1950's; since then, cutting for poles, pulp, and lumber has increased to an estimated 7,000 acres annually.[1]

Herbaceous growth develops after clearcutting and provides a potentially important grazing resource for approximately 20 years while the new timber stand is developing. Livestock and game animals now graze some clearcut areas, but the grazing potential appears to be considerably underutilized. This incomplete use is the result of several administrative factors, chief among which are a limited knowledge of the grazing resource, and a tendency to ignore it because of its transitory nature.

Efficient management of these ranges depends largely upon our ability to predict the expected composition, yield, and persistence of forage on clearcuts from selected environmental factors. Findings from a study aimed at providing the basis for prediction are presented here.

Methods

FIELD AND LABORATORY METHODS

This study was limited to unthinned, lower elevation (below 7,500 feet) clearcut-and-burned areas in Montana, east of the Continental Divide. Twenty-five clearcut sites within the Lewis and Clark and the Gallatin National Forests were selected to represent a range in post-clearcut ages (2 to 17 years had elapsed since cutting) and a variety of aspects.

On each of these sites, the percentage of aerial crown cover was estimated for each understory plant species within thirty circular plots which were 4.8 sq. ft. in size and distributed in a random pattern over a 1-acre macroplot. All herbaceous vegetation within the circular plots was clipped at ground level near the end of the growing season, dried at 60° C. for 24 hours, and weighed. The center of each circular plot served also as the center of a milacre plot for data on tree regeneration.

Physical and chemical characteristics of the A and B soil horizons were determined from samples taken from two soil pits on each of the 25 sites.

We approximated site index for lodgepole pine for 19 of the 25 sampled sites from measures of site index, as described by Alexander (1966), on immediately adjacent, uncut stands that closely matched the clearcut areas in soils and topographic features.

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[1]From files of USDA Forest Service, Northern Region, Missoula, Montana.

ANALYSIS

Successive, full-screen,[2] multiple regression sets enabled us to identify combinations of environmental factors that substantially affect forage production. Final acceptance of such combinations was conditioned by agreement of the algebraic signs of estimated effects with those of expected[3] effects, under least squares fit. In these analyses, average dry weight in pounds (or yield) per acre was the dependent variable, and 37 environmental factors constituted the complete set of independent variables (listed below):

A. *Time (Number of Years Since Clearcutting)*

B. *Tree Factors (Regeneration):*

Density of Lodgepole Pine, determined by actual count

Density of All Trees, determined by actual count

Percent Canopy Cover of Lodgepole Pine

Percent Canopy Cover of All Trees

Stocking Rate of Lodgepole Pine, expressed as a percent of milacre plots in which a tree occurs

Stocking Rate of All Tree Species

Average Height of Lodgepole Pine Reproduction, estimated to nearest 1/2 foot

Average Height of All Trees

C. *Site Index*

D. *Topographic Factors:*

Percent Slope

Elevation

Cosine of Azimuth +1, expressed in 2 π radians

Cosine of Azimuth +sine azimuth +2, expressed in 2 π radians

E. *Soil Factors:*

Each of the following represents two variables, one for the A horizon and one for the B horizon:

Field Capacity, estimated by moisture retention at 1/3-atmosphere of pressure, using standard pressure membrane apparatus and procedures outlined by Richards (1954).

---

[2]The dependent variable is fitted as a function of each of all combinations of specified groups of independent variables via computer. R^2, the Coefficient of Determination, is printed out for each regression.

[3]"Expected" from prior knowledge.

Wilting Point, estimated by moisture retention at 15-atmospheres of pressure, using standard pressure plate apparatus.

Percent Sand, determined by hydrometer method.

Percent Silt, determined by hydrometer method.

Percent Clay, determined by hydrometer method.

Available Potassium, determined by flame photometer.

Percent Organic Matter, measured by Walkely-Black wet digestion chromic acid method (Jackson 1958).

Total Nitrogen, measured by the micro-Kjeldahl method, using $CuSO_4$ and Na_2SO_4 digestion mixture.

Bulk Density, measured by the paraffin coating technique.

Soil Reaction, or pH, measured with a glass electrode in a saturated paste.

Horizon Thickness, measured in the field.

Water Holding Capacity, estimated by the difference between field capacity and wilting point, and weighted by horizon thickness, rock content, and percent fine material.

Results and Discussion

Understory yields ranged from about 100 to 1,200 lbs./acre (dry weight), and averaged 644 lbs./acre.

TIME

Understory production is expected to be low, both immediately after logging and after canopy closure of the reproducing lodgepole pine stand. Between these two points in time, production should peak. This trend was strongly evident within the 17-year age span of the plots, and was approximated by the sigmoid function, e^{-k}, where $e = 2.718$ and $k = 0.01667 (\text{age of cut minus age at peak production})^2$. So the time effect was retained as a component of all models examined.

Total understory production reached its peak about 11 years after clearcutting. The several vegetal classes, however, performed differently with time (fig. 1). Sedge was the only class that showed no discernible pattern; its mean is shown in figure 1. The regression for grasses was not significant ($P > .05$), but the data suggest slight peaking at about 13 years. The regressions for forbs and shrubs were significant ($P < .05$). Forb production peaked at 10 years. Shrub production increased over the entire range of time, but the increase was slower after 11 years than it was previously, and there is a slight but unconfirmed hint of a flattening of production at about 15 or 16 years after clearcutting. These production patterns were determined on sites supporting unthinned lodgepole pine reproduction. Observations in other clearcuts where reproduction had been thinned suggest that thinning may delay the peaking of understory production a few years. If this is true, a grazing potential of perhaps 20 years, or more, may be expected on clearcuts where tree regeneration is thinned.

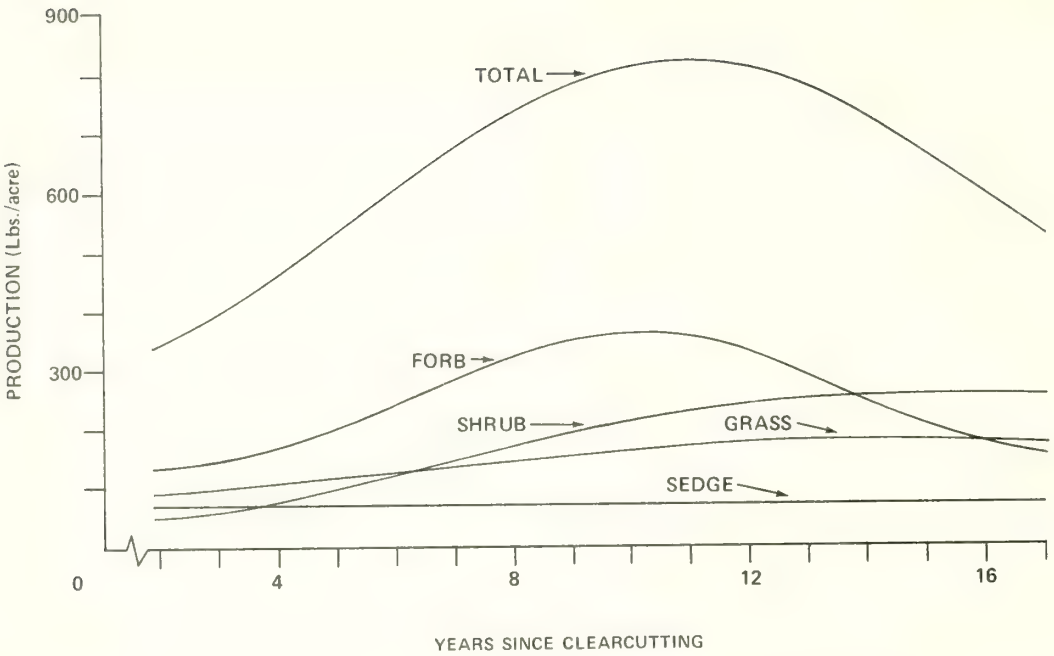

Figure 1.--Trends in understory production on lodgepole pine clearcuts as affected by time.

The concurrent increase in shrub production and decrease in herbaceous plants is attributed to grouse whortleberry (*Vaccinium scoparium*) which constituted about one-half of the shrub cover on these sites. The roots of grouse whortleberry lie mostly within 2 or 3 inches of the soil surface. This soil zone is freer of roots of the other vegetation than are the deeper zones; also, it is often the sole recipient of moisture from light summer rains. The competitive advantage thus accorded grouse whortleberry enables it to prosper at the expense of the other understory plants.

Except for scattered individuals of other shrub species, grouse whortleberry is often the sole shrub in older stands of lodgepole, where it often dominates the understory.

TREE FACTORS

Tree regeneration variables are highly unstable quantities for a few years after clearcutting; thus, they are of limited usefulness for predicting yields of understory vegetation. They are of interest, however, because they do affect these yields.

The general trend of production with time conforms to expectation. As tree canopies thicken and root systems expand, understory vegetation succumbs to the increasing competition for light and moisture, as evidenced by the usual paucity of understory plants in overstocked stands of lodgepole pine that are at the sapling-or-older stage of development.

BASILE JOSEPH V. and JENSEN CHESTER E.

1971. Grazing potential on lodgepole pine clearcuts in Montana, USDA Forest Serv. Res. Pap. INT-98, 11 p., illus.

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In this study, lodgepole regeneration reached the early sapling stage on only three clearcuts, the youngest of which was 14 years old. Herbage yields, however, started to decline on 10- and 11-year-old clearcuts where tree heights averaged only 2 feet. Apparently, then, lodgepole pine adversely affects herbaceous plants while still in the seedling stage. Moreover, we believe competition for light was negligible on the sampled sites because the maximum tree canopy cover was only 37 percent and averaged a mere 7 percent. After discounting the time effect, tree canopy and understory yield were not significantly correlated.

Very likely the roots of seedling trees had developed sufficiently by 10 years of age to gain a competitive advantage over herbaceous plants for available moisture. Horton (1958) reported that open-grown lodgepole exhibited about a 1:1 ratio of maximum lateral root length to stem height for the first 20 years. If the 1:1 ratio applies to trees in this study, in which stem heights averaged 2 feet, roots should have radiated as far as 2 feet from the stem. Because lodgepole pine density averaged 5,800 stems per acre, then uniformly distributed trees would be spaced about 33 inches apart. Thus, the roots of a given tree would overlap those of its immediate neighbors by about 1 foot. Apparently, then, we could apply to our study sites Horton's statement that "in a fully-stocked condition, all of the available rooting space is presumably utilized so that a complex interweaving network of roots occurs." Also, we could assume that this network of tree roots would compete effectively with understory plants for soil moisture.

Of course, trees were not uniformly distributed on the clearcut sites, but the added effect of stocking rates on accountable variation in forage yields was sufficiently high to suggest considerable overlapping of root systems:

	R^2
yield = f (time)	0.38
yield = f (time + % stocking of lodgepole)	.47
yield = f (time + % stocking of all trees)	.55

Further additions of tree density or of tree canopy cover, or both, failed to raise R^2 above 0.56.

SITE INDEX

Ideally, a prediction model should be based on variables for which measurements are easily obtained. Accordingly, we examined the suitability of site index for predicting understory yield. For this prediction, we used data from the 19 clearcuts for which site index could be approximated from the immediately adjacent uncut stands.

After fitting the time effect, site index accounted for 1 percent of the variation in yield. As an additive or interacting term with additional variables in the model, the contribution of site index to accountable variation was still too small to warrant its retention in prediction models. Apparently this measure of site potential for tree growth was not closely related to the production of associated understory vegetation.

TOPOGRAPHIC FACTORS

As sole additive components to the "yield = f (time)" equation, slope accounted for an additional 20 percent of the variation, elevation for 11 percent, and aspect for less than 1 percent.

This response to slope is interesting. One usually finds increasing slope steepness associated with shallower and rockier soils and greater runoff, and therefore with decreasing herbage production; but in this study, contrary to expectations, understory production responded positively to slope. In addition, the data revealed a strong coincidence of the higher slope values with the more moist sites whose expected influence on yield is positive. This confounding of slope with other variables cast doubt on the validity of using slope for predictive purposes in other areas; thus, it was eliminated from further consideration.

The remaining topographic variables, elevation and aspect, were added to the "yield = f (time)" equation and this resulted in R^2 values as follows:

yield = f (time)	0.38
yield = f (time + elevation)	.49
yield = f (time + elevation + aspect)	.51

When added to more complex models, elevation did not contribute sufficiently to R^2 values to warrant its retention.

The effect of aspect was tested two ways: as cosine azimuth + 1, which places minimum expected yields at due south; and as cosine azimuth + sine azimuth + 2, which places minimum expected yields at southwest. Discounting the time effect, neither of these components contributed materially (less than 2 percent) to accountable variation.

SOIL FACTORS

The influence of moisture on understory production was emphasized by the additive contribution of field capacity of the A and B horizons to the "yield = f (time)" equation, with $R^2 = 0.74$. The further addition of sand content of the A horizon, another moisture-related variable, produced the equation

$$\text{Yield} = -251.4000 + 383.5379\, e^{-\frac{(1-11)^2}{60}} + 3.1646FC_A$$

$$+ 16.8020FC_B + 291.7550\, e^{-\frac{|Sand_A - 55|^{2.5}}{1,200}}$$

with $R^2 = 0.79$. Contributions of other soil variables added to this model were negligible.

Wilting point could be substituted for field capacity in this and in alternative models with little sacrifice in R^2 values. However, the addition of wilting point did not improve any model containing field capacity.

Available potassium (K) in the soil solum ranked second only to the field capacity and wilting point variables in degree of correlation with understory yields, and produced an R^2 of 0.73 when added to the "yield = f (time)" equation. The further additions of sand content of the A and B horizons raised the R^2 to 0.81. However, equally satisfactory results were obtained with the potassium and sand values of the B horizon only:

	R^2
yield = f (time)	0.38
yield = f (time + K_B)	.70
yield = f (time + K_B + $Sand_B$)	.80

as in the equation

$$Yield = -228.051 + 588.614\, e^{-\frac{(T-11)^2}{60}} + 1.702\, K_B + 282.783\, e^{-\frac{|Sand_B - 55|^{2.5}}{1,200}}$$

Holmes and Tackle (1962) found exchangeable potassium in the B horizons to be noncorrelated with heights of dominant lodgepole pine trees (r = 0.055). In this study, potassium in the B horizon was not significantly correlated with site index for lodgepole pine (r = 0.37), but potassium in the A horizon was significantly correlated ($P < .05$) with site index (r = 0.46). A modest correlation with site index plus a marked effect on understory yields suggests that fertilizing with potassium may be beneficial both to understory production and to growth rates of lodgepole pine.

The two above equations may serve as interim predictors of understory yield. The response surfaces of these equations over the full ranges of time and sand content are shown in figures 2 and 3 for the extremes of field capacity and of potassium, respectively. In both instances, the change between surfaces is linear between the two extremes shown for the third independent variable. Being additive, the models may not fit too well near the left edge of the surfaces, since the expectation would be for these to come closer together near time 0. Nonetheless, they do emphasize the substantial effect of field capacity and of potassium on understory yields.

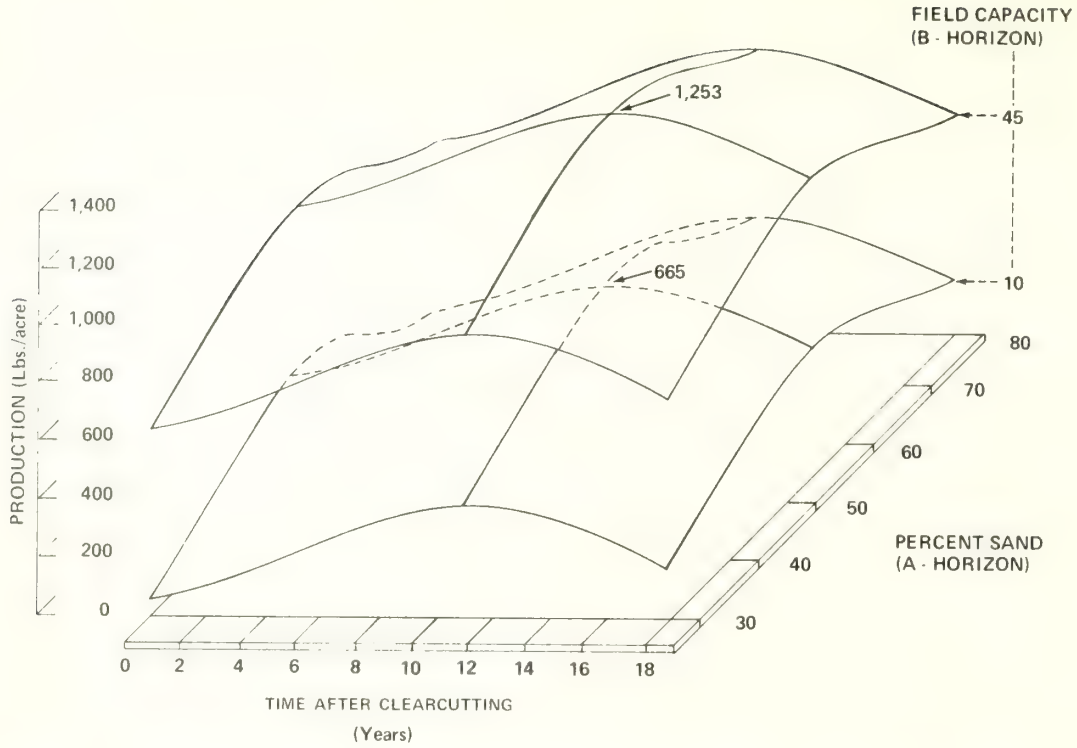

Figure 2.--Response surfaces at extremes of field capacity, showing the relations between understory production, time after clearcutting, and percent sand.

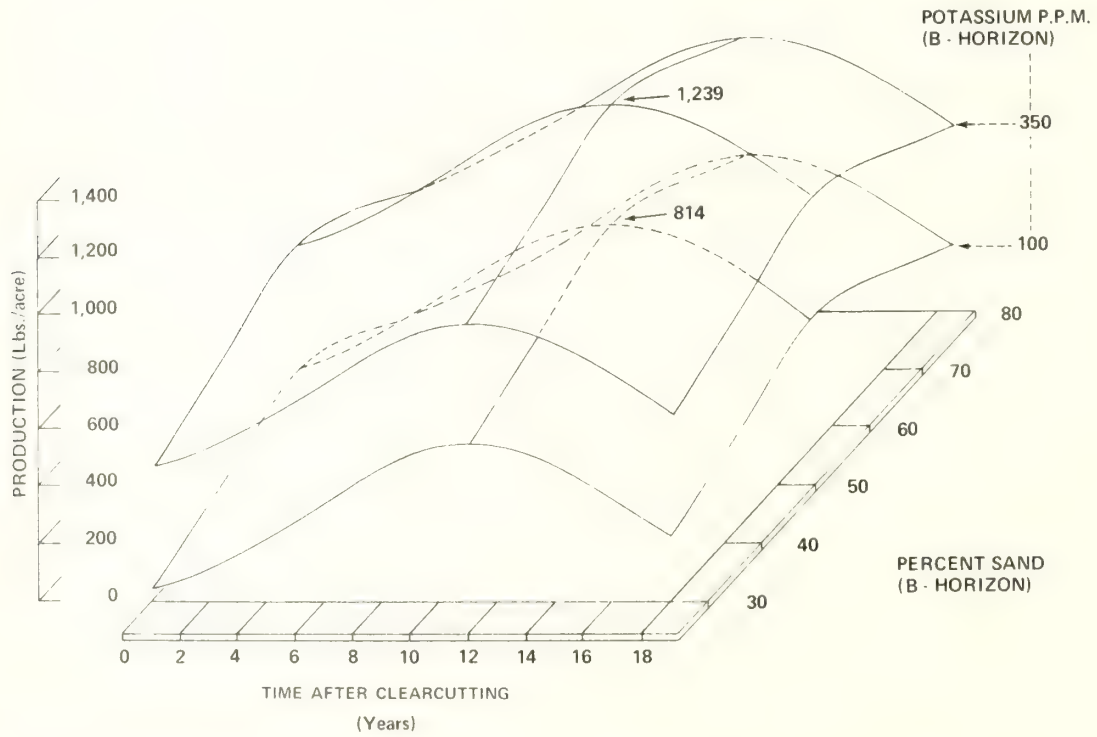

Figure 3.--Response surfaces at extremes of potassium content, showing the relations between understory production, time after clearcutting, and percent sand.

FORAGE VALUE

Major species of the understory vegetation are given in table 1. We computed species composition on each site from percentage aerial crown cover. Separate palatability ratings for cattle, sheep, and elk were assigned to each of the species that contributed 3 percent, or more, to the cover on at least one site. Ratings ranged from 0 to 6, with a 0 rating for unpalatable plants and a 6 rating for excellent species. Species contributing less than 3 percent of the cover were arbitrarily rated 3, about midway in the scale. Sources consulted for information on palatability included Dayton (1960), Hayes and Garrison (1960), Hermann (1966), and USDA Forest Service (1937).

Table 1.--*Composition, aerial crown cover, and frequency of vegetation on lodgepole pine clearcuts. Includes only those species contributing 3 percent or more to the vegetal cover on at least one site and occurring on at least 4 of the 25 sampled sites*

Species	No. of sites	% Frequency		% Composition		% Aerial cover	
		Avg.	Range	Avg.	Range	Avg.	Range
FORBS							
Antennaria racemosa	16	22	3-53	2	Tr-6	1	Tr-2
Arnica cordifolia	23	64	13-100	7	1-24	2	Tr-9
Aster spp.	22	37	3-100	6	Tr-23	2	Tr-11
Epilobium angustifolium	22	47	3-100	9	Tr-26	3	Tr-9
Erigeron spp.	5	19	7-37	2	Tr-6	1	Tr-2
Erythronium grandiflorum	9	41	7-97	1	Tr-5	Tr	Tr-1
Fragaria spp.	20	22	3-67	3	Tr-12	1	Tr-5
Galium boreale	7	20	3-80	1	Tr-6	Tr	Tr-3
Hieracium cynoglossoides	24	42	3-83	2	Tr-7	Tr	Tr-2
Heuchera cylindrica	7	10	3-40	1	Tr-5	Tr	Tr-1
Linnaea borealis	5	29	3-60	3	Tr-8	2	Tr-4
Lupinus spp.	24	47	3-97	10	Tr-38	4	Tr-20
Taraxacum officinale	20	17	3-53	1	Tr-3	Tr	Tr-2
Thalictrum ruderale	5	16	3-43	3	Tr-7	1	Tr-3
GRASSES AND SEDGE							
Carex geyeri	25	63	37-93	10	2-42	3	Tr-9
Agrostis spp.	14	24	3-53	3	Tr-14	1	Tr-11
Calamagrostis rubescens	14	69	7-100	15	Tr-36	3	Tr-12
Calamagrostis spp.	7	15	3-70	5	TR-16	2	Tr-7
Phleum pratense	4	22	3-50	2	Tr-4	Tr	Tr-2
Trisetum spicatum	16	34	3-90	2	Tr-5	1	Tr-2
TREES AND SHRUBS							
Arctostaphylos uva-ursi	7	19	3-50	4	Tr-17	1	Tr-4
Juniperus communis	10	10	3-23	3	Tr-10	1	Tr-4
Rosa spp.	12	29	3-70	2	Tr-5	1	Tr-2
Spiraea betulifolia	23	52	7-87	7	1-17	2	Tr-7
Vaccinium scoparium	22	74	30-100	18	2-36	6	Tr-17

The percent composition of each understory species was multiplied by its palatability rating, and the sum of these resultant products was divided by 100 to arrive at an average palatability rating for all understory vegetation. Based on the 0 to 6 scale, average palatability ratings were approximately 1.7 for cattle, 2.0 for sheep, and 2.4 for elk--in other words, fair for cattle and sheep, and only slightly better for elk. Because of the widespread occurrence and appreciable amounts of lupine on clearcut areas, sheep grazing might be hazardous.

Conclusions

Clearcutting, and thinning of subsequent lodgepole pine regeneration, stimulates forage production that may provide a grazing resource for livestock and big game for an estimated 20 years or more. A harvest of 10,000 acres/year of lodgepole pine in Montana appears probable in the near future. Thus, the lodgepole pine type represents a grazing potential of nearly 1/4 million acres on a sustained basis. This impressive grazing potential warrants an upgrading of the less impressive yields (average peak production was about 800-1,000 lbs./acre) and palatability (fair) of the indigenous plant cover. For purposes of such upgrading, it is desirable to conduct seeding studies on ways to increase forage yields and palatability without adversely affecting timber management objectives.

Where indigenous vegetation is to be grazed, gross estimates of potential production, and its change over a period of time, are possible with the interim prediction equations presented here. These estimates permit an appraisal of grazing potentials in advance of timber cutting and probably will allow better integration of grazing use on clearcuts with that on permanent range.

If seeding of clearcuts is contemplated, the prediction equations will be helpful in the judicious allocation of monies to those sites offering maximum returns on investment.

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USDA Forest Service
Research Paper INT-99
1971

WEATHER VARIATIONS ON A MOUNTAIN GRASSLAND IN SOUTHWESTERN MONTANA

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ABSTRACT

Weather data collected on mountain grasslands during five growing seasons are summarized. These data are from four stations on opposing exposures (southwest and northeast) at different elevations (7,100 and 8,200 feet). Tabular and graphic data presented are for the station on the 7,100-foot southwest exposure only. These data include information on: solar radiation, wind, precipitation, air temperature, and relative humidity; exposed and shaded soil surface temperatures, and soil temperatures and moisture trends at three depths. Summaries include: means, ranges, extremes, and durations. Differences in weather on the two exposures and at the two elevations are discussed. Air temperature and precipitation records are compared with those obtained from two U.S. Weather Bureau stations located in nearby valleys.

Introduction

An understanding of mountain grassland ecosystems requires knowledge of both the dynamic interaction between plants and of the effects of environment and environmental variation upon those plants. Climate and variations in weather are unquestionably among the environmental factors that most affect mountain grasslands.

Our knowledge of mountain weather is sketchy at best. The influence of mountain topography on weather renders extrapolation of records from valley stations to mountain slopes hazardous. The only reliable means of gathering such information is to locate weather stations on mountain slopes, which has been done to only a limited extent in various parts of the West.

Some information on weather has been obtained in the course of relatively short term ecological studies, most of which have been concerned with the subalpine and alpine zones. For example, Klikoff (1965) obtained two summers of weather data from a timberline basin (elevation, 12,000+ feet) in Yosemite National Park, Calif. Summer weather data were also collected during ecological studies in the alpine areas (elevation, 11,000 feet) of Rocky Mountain National Park, Colo. (Holway and Ward 1964; Salisbury et al. 1968), and in the Medicine Bow Mountains of southeastern Wyoming (Bliss 1956; Scott and Billings 1964). Mountain weather data were recorded for two summers at somewhat lower elevations (7,000 and 9,000 feet) by Patten (1963) during an ecological study in the Madison Range of southwestern Montana.

Relatively long term weather summaries have been published for a few high mountain locations. These include year-round records maintained for 19 years at elevations of 10,500 feet and for 15 years at 12,470 feet in the White Mountains of Calif. (Pace et al.1968), and for 6 years at elevations ranging from 7,200 to 12,300 feet on the Front Range near Boulder, Colo. (Marr et al. 1968). In addition, Judson (1965) has published 15 years of winter and spring weather data for Berthoud Pass, Colo., which has an elevation of 11,315 feet.

No published data are available describing in detail climatic conditions and weather variations within the intermediate elevation (7,000-9,000 feet) mountain grassland areas of southwestern Montana. Patten (1963) reported on weather from the same general area, but his data were limited both in detail and duration.

Ecological studies of mountain grasslands necessitated acquisition of such weather information. Consequently, four stations were established to record weather data considered to be of ecological significance to mountain grasslands. Summaries of these data are presented here for those specifically interested in the effects of climate and weather variations on this vegetation type and for those interested in mountain weather in general.

Background Information

The four stations selected for observing variations in mountain grassland weather were near the north end of the Gravelly Range, Madison County, in southwestern Montana. The Gravelly Range of mountains has a generally rounded crest and a number of points extending above 9,000 feet in elevation. Its north-south axis is approximately 30 miles long. Toward the west, the Ruby River separates the Gravelly Range from the equally high north-south Snowcrest Range. Toward the east, the Madison River separates the Gravelly Range from the Madison Range, which has numerous peaks rising well over 10,000 feet.

Two stations were placed on facing slopes (lat. 45°09' N., long. 111°48' W.) at an elevation of 7,100 feet on the east flank of the Gravelly Range. One was on a gently sloping southwest exposure; the other, 200 yards southwest of the first, was on a gently sloping northeast exposure. Two more stations straddled the crest (lat. 45°07' N., long. 111°52' W.) of the Gravelly Range at an elevation of 8,200 feet. One was on a gently sloping northeast exposure on the east side of the crest; the other, approximately 700 yards southwest of the first, was on a gently sloping southwest exposure on the west side of the crest. The upper stations were approximately 5 miles southwest of the two lower ones.

All four stations were on natural mountain grasslands where the vegetation, a mixture of low-growing grasses and forbs, seldom exceeds 12 inches in height. Generally, Idaho fescue (*Festuca idahoensis*) is the dominant species. Occasional patches of sagebrush (*Artemisia tridentata*) occur on the deeper soils. The grasslands at the lower elevation are interspersed with stands of Douglas-fir (*Pseudotsuga menziesii*) and limber pine (*Pinus flexilis*). Grasslands at the upper elevation are interspersed with stands of limber pine, lodgepole pine (*Pinus contorta*), and subalpine fir (*Abies lasiocarpa*). Nowhere were trees closer than about 100 yards to the weather stations.

Instrumentation

All four stations were equipped with similar weather-measuring instruments; two exceptions will be mentioned later. All equipment was placed within a 20- by 40-foot, four-strand barbed wire enclosure.

Air temperature and relative humidity were recorded continuously by a 7-day hygrothermograph, installed 4-1/2 feet above the ground in a standard Weather Bureau instrument shelter.

Soil surface temperatures were measured continuously by a 7-day thermograph. The sensor bulbs of the thermograph were 1/2- by 8-inch lead-covered cylinders attached to mercury-filled Bordon mechanisms by 10-foot steel capillary tubes. One sensor was placed in a permanent position on the soil surface in perpetual shade, another, in the sun. The shaded sensor was beneath a well-ventilated, double-slatted aluminum shade. The shade was about 5 inches above the sensor bulb and completely sheltered it from direct sunlight. The sensor fully exposed to the sun was placed on a cultivated soil surface that was free of vegetation. The bulb of this sensor was lightly coated with soil particles to give its surface the color and texture of soil.

Additionally, duplicate readings were taken of soil temperatures each week at depths of 20 cm. (8 inches), 50 cm. (20 inches), and 100 cm. (39 inches). These temperatures were measured by thermistors within Colman fiberglass soil-moisture units permanently installed at the three depths. The thermistors were usually read between 11:00 a.m. and 2:00 p.m. each Monday.

Soil moisture readings in duplicate were also obtained at weekly intervals at the three already designated depths. Soil moisture was determined from the amount of electrical resistance within Colman fiberglass soil-moisture units buried in undisturbed soil beneath existing vegetation. Laboratory calibration of the Colman units in undisturbed soil cores, taken from each level of unit placement in the field permitted conversion of electrical resistance to approximate percent moisture.

Each week, precipitation totals at all stations were recorded from unshielded standard rain gage cans. A protective film of oil effectively curtailed evaporation. These records were used to compare differences in precipitation between exposures.

Recording precipitation gages measured periodicity, intensity, and duration, as well as total fall at stations on the southwest exposure at both elevations. These gages, the weighing type (Belfort, Model 5-780), traced a continuous 7-day record. Metal deflectors shielded both from wind currents.

Solar radiation was measured by bimetallic actinographs (Kahlsico, Model SO-28) on the southwest exposure at both elevations. The combined measures, diffuse sky radiation and direct solar radiation, are expressed as both maximum intensity and as total energy received per day.

The amount of wind each station received was measured by totalizing, 3-cup anemometers mounted 6 feet above the ground. These were read weekly. Data are expressed as average miles per hour per week.

Weather records were collected at all stations during five growing seasons (1964 through 1968). Those for the stations at the 7,100-foot elevation were recorded from May 1 to November 1. Usually, the winter snowpack has melted from the southwest exposures at this elevation by late April and from the northeast exposures by early May. Although occasional snowstorms are not unusual in May, June, September, and October, the winter snowpack generally does not begin to form until sometime in November.

Weather records for the stations at the 8,200-foot elevation were begun as soon as the areas were reasonably accessible, anytime during the first 2 weeks of June. The winter snowpack generally had melted from the southwest exposures at this elevation by early June and from the northeast exposures by about mid-June. Although snowstorms can occur at this elevation any month of the year, the winter snowpack usually does not begin to form until sometime in October. Thus, the weather records for the two upper stations covered approximately 3-1/2 months each year and those for the lower stations about 6 months of each study year.

The tabular and graphic data published here are for one station only, that on the southwest exposure at the 7,100-foot elevation. Differences between exposures and between elevations are discussed in the text.

Data from U.S. Weather Bureau stations permitted comparisons of monthly means of daily maximums, means of daily minimums, and the highest and lowest temperatures reached during the month. Precipitation comparisons are of total amounts received during monthly periods. Data for all comparisons cover the growing seasons from 1964 through 1968.

Solar Radiation

Over the 5 study years, maximum intensity of solar radiation at the 7,100-foot station on the southwest exposure during the months of May, June, and July averaged slightly over 1.40 cal./cm.^{2}/min. (table 1). As expected, this daily maximum dropped gradually from the summer solstice until the end of October when it averaged 0.85 cal./cm.^{2}/min. (fig. 1). At no time did the yearly variation of monthly averages exceed 0.20 cal./cm.^{2}/min.

No consistent difference in maximum radiation intensity was recorded between the 7,100-foot and the 8,200-foot elevations, although we had anticipated greater intensity at higher elevations as atmospheric absorption of solar energy diminished. Apparently, our instruments were insensitive to the difference caused by the 1,100-foot elevational spread.

The total solar energy received per day was greatest during July and gradually decreased until observations ceased at the end of October (fig. 1). The average daily insolation, 255 cal./cm.^{2}, received in October, was less than half of that received in July (table 2). The greater daily variability of total insolation in May and June than in succeeding months reflects the changeability of weather during the early part of the growing season. The extreme range in total radiation is of particular interest. Over the 5-year period, the absolute maximum for any one day was 684 langleys recorded the last week of June 1966; the absolute minimum for late June (1968) was only 191 langleys (fig. 2). The lowest total radiation (49 langleys) for a 24-hour period was recorded in late September 1965. Such wide differences in solar radiation should have a profound influence on the daily cycle of plant growth on these mountainous areas.

Table 1.--*Average*[1] *daily maximum solar radiation intensity at the station on the southwest exposure at the 7,100-foot elevation*

Year	May	June	July	Aug.	Sept.	Oct.
			Cal./cm.^{2}/min.			
1964	1.35	1.43	1.33	1.29	1.18	0.92
1965	1.42	1.40	1.45	1.37	1.04	.97
1966	1.40	1.51	1.41	1.37	1.18	.90
1967	1.43	1.43	1.43	1.33	1.24	.97
1968	1.46	1.34	1.41	1.26	1.21	.97
5-year mean:	1.42	1.42	1.41	1.32	1.17	.95

[1]Standard deviation of monthly means averaged 0.20 cal./cm.^{2}/min.

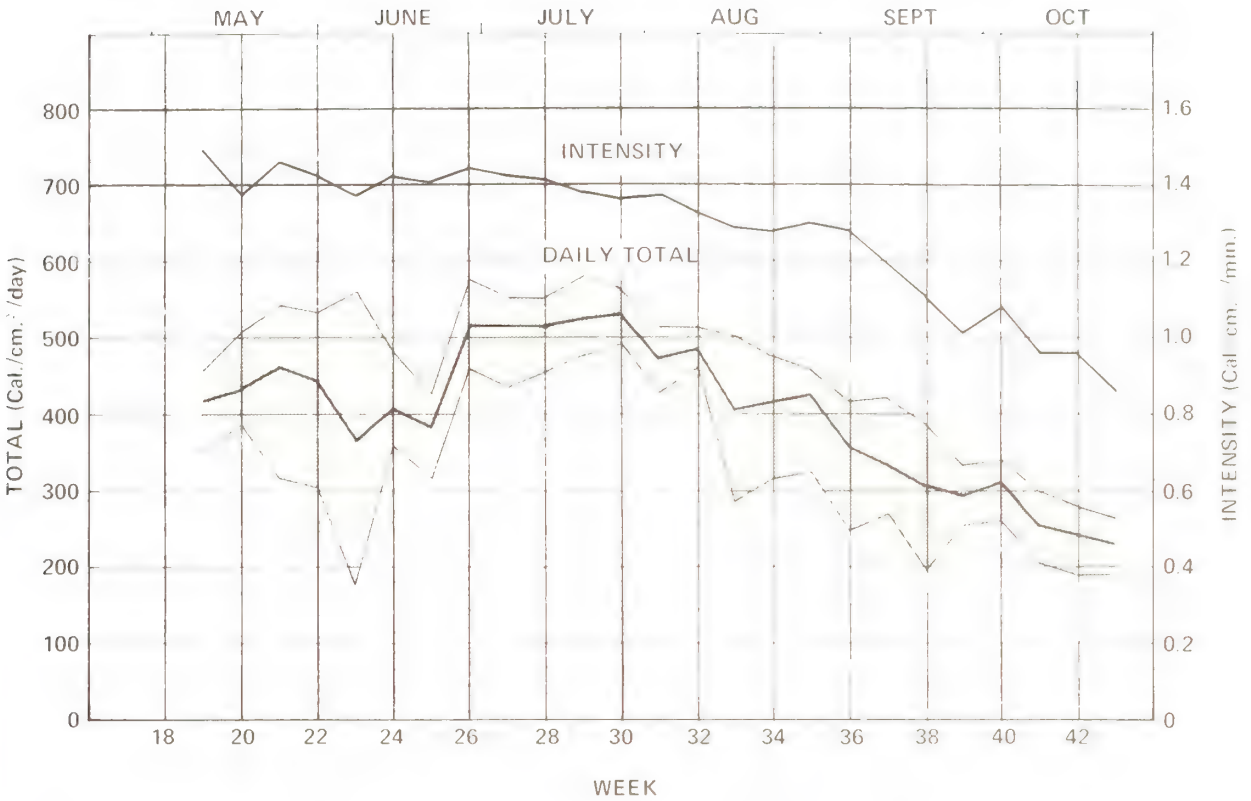

Figure 1.--Solar radiation at the station on the southwest exposure at 7,100 feet elevation: 5-year average of weekly means of daily totals; the range of weekly means over 5 years; and weekly means of daily maximum intensity.

Table 2.--*Average*[1] *daily solar radiation at the station on the southwest exposure at the 7,100-foot elevation*

Year	May	June	July	Aug.	Sept.	Oct.
	- - - - - - - - *Cal./cm.*^{2}*/day*- - - - - - - - -					
1964	391	396	516	416	351	260
1965	430	449	518	435	276	295
1966	488	451	531	454	356	240
1967	480	411	502	496	373	241
1968	415	401	535	387	310	237
5-year mean:	444	423	520	438	333	255

[1]Standard deviation for monthly means averaged 115 cal./cm.^{2}/day.

Total radiation received at 8,200 feet did not differ appreciably from that received at 7,100 feet. As mentioned previously, this may reflect the inability of the instruments to measure the comparatively small difference involved.

The charts produced by the actinographs clearly showed the passage of cloud shadows over the sensing device. Consequently, a measure of relative cloudiness on individual days was possible. Table 3 gives the 5-year percentage of days per month that were virtually cloud-free (no more than two brief shadow occurrences). Cloud-free days averaged 9 and 7 percent for May and June, respectively. The number of cloud-free days began to increase in July and by September and October, about one-fourth of the days were virtually cloud-free. As might be expected, the variation between years was considerable; some years had over twice as many cloud-free days during the same month as others.

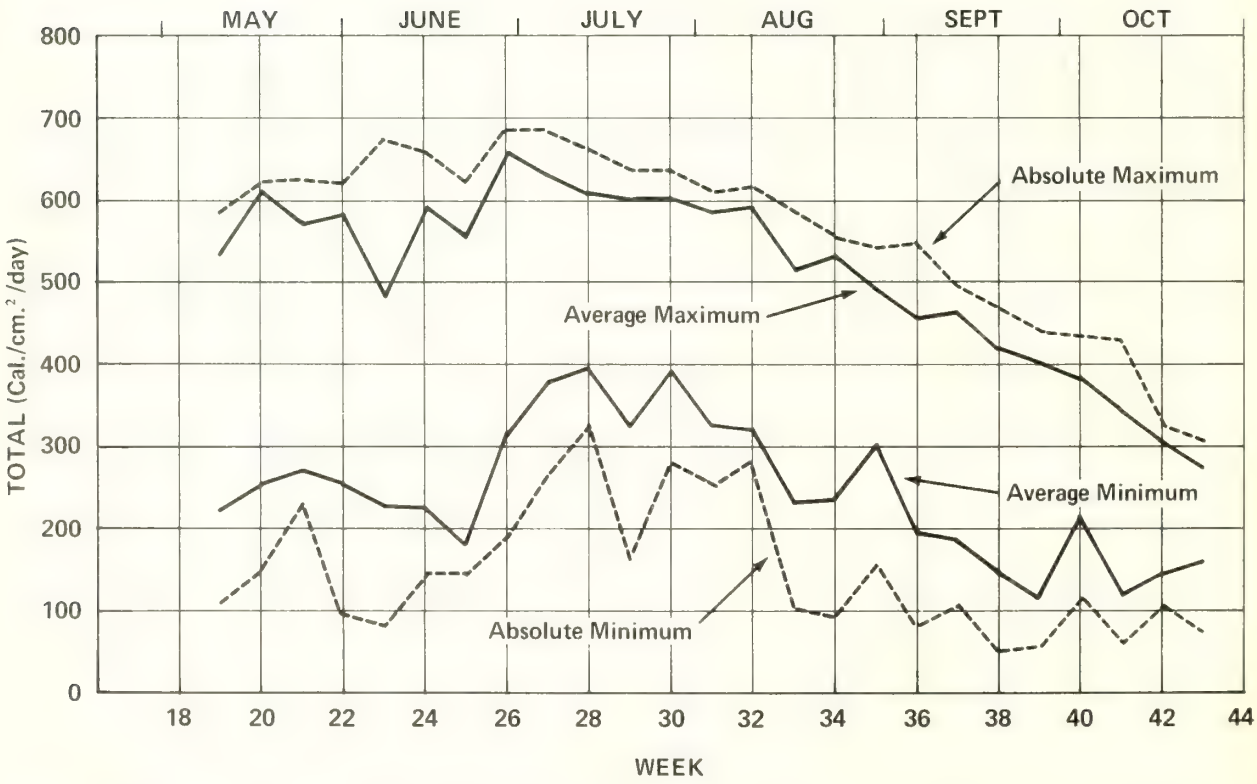

Figure 2.--Solar radiation at the station on the southwest exposure at 7,100 feet elevation: absolute maximum and absolute minimum daily radiation and average maximum and minimum daily radiation received over 5-year period.

Table 3.--*Percent of virtually cloud-free days at the station on the southwest exposure at the 7,100-foot elevation*

Year	May	June	July	Aug.	Sept.	Oct.
	- - - - - - - - - -		*Percent*	- - - - - - - - - -		
1964	10	3	32	23	27	48
1965	12	13	19	13	20	29
1966	10	3	10	16	17	25
1967	9	7	10	32	23	20
1968	3	7	16	16	23	25
5-year mean:	9	7	17	21	22	29

Air Temperature

Averaged by weeks, daily maximum air temperatures increased gradually from somewhere between 41° and 56° F. in early May to somewhere between 71° and 81° F. in late July and early August (fig. 3). A conspicuous dip in early June corresponds to a decrease in total solar radiation for the same period. By late October, daily maximum temperatures approximated those of early May. The drop in maximum air temperatures lagged about 2 weeks behind the decrease in total daily solar radiation.

The absolute maximum air temperature (86° F.) reached over the 5-year period occurred July 30, 1966. However, maximum temperatures close to this high were recorded through August and into early September (fig. 4). In contrast, maximum temperatures never exceeded 75° F. in May or 80° F. in June. The average maximum temperatures for each month (table 4) were always about 20° F. lower than the absolute maximums for that month over the 5-year period. The variability in maximum air temperatures between years was greatest in late May, early June, late August, and early September (fig. 4). This reflects the unstable weather that characteristically occurs during these periods in southwestern Montana.

The curve for average minimum air temperatures generally paralleled that for average maximum temperatures, but was from 20° to 30° F. lower (fig. 3). The greatest differences between maximum and minimum temperatures were recorded in July and early August. Average minimum temperatures did not rise above freezing until about mid-May and by mid-October, average nighttime temperatures were again below freezing. At no time did the weekly averages of minimum temperatures rise above 51° F.

July was the only month during the 5-year period when the absolute minimum temperature did not drop to freezing or below. Variation of minimum temperatures between years was greatest in late August and September (fig. 4).

Duration of a temperature extreme is probably just as important to the physiological processes of plants as the extreme itself. An expression of this duration was obtained by determining the amount of time the temperature remained within 5° F. of the extreme. Monthly averages of the duration of daily maximum temperatures ranged between 5.2 and 7.6 hours (table 5). July was the only month in which durations of both maximum and minimum temperatures were about equal. In the other months, minimum temperatures always lasted longer than the maximum.

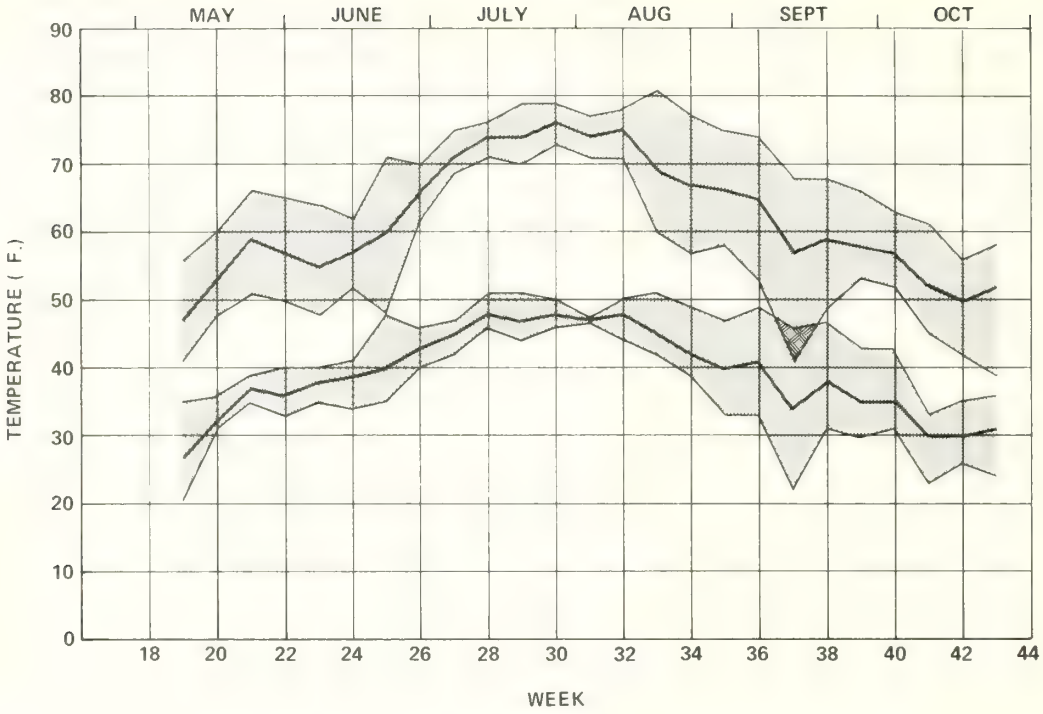

Figure 3.--Air temperature at the station on the southwest exposure at 7,100 feet elevation: 5-year averages of weekly means and range of daily maximums; and averages of weekly means and range of daily minimums.

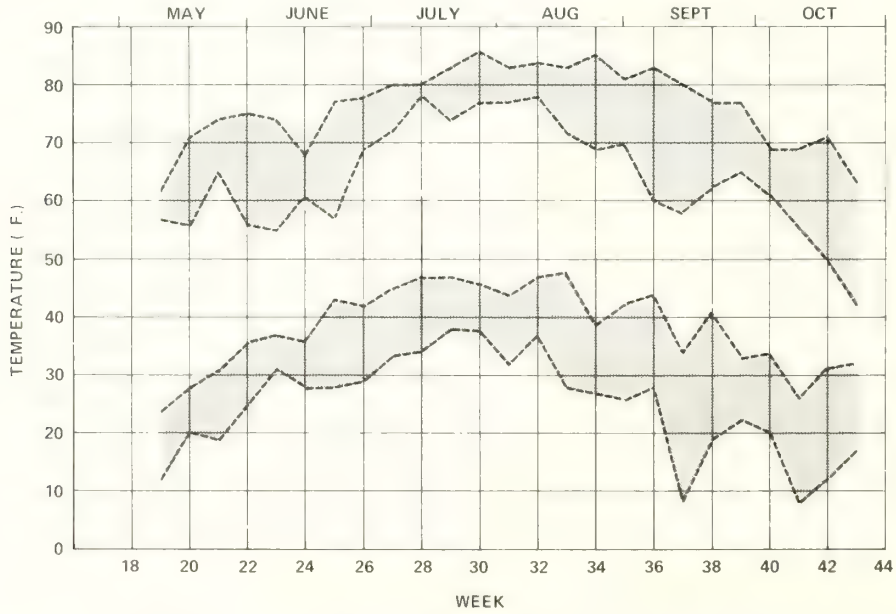

Figure 4.--Air temperature at the station on the southwest exposure at 7,100 feet elevation: range in absolute maximum and minimum temperatures over 5-year period.

Table 4.--*Average*[1] *daily maximum and minimum temperatures at the station on the southwest exposure at the 7,100-foot elevation*

Year	May	June	July	Aug.	Sept.	Oct.
			°F.			
1964 Max.	55	[illegible]	74	69	59	[illegible]
Min.	[illegible]	38	46	41	[illegible]	[illegible]
1965 Max.	49	61	70	68	49	[illegible]
Min.	31	40	46	44	30	37
1966 Max.	59	[illegible]	76	71	66	49
Min.	35	38	47	[illegible]	[illegible]	29
1967 Max.	57	57	72	76	67	49
Min.	[illegible]	39	48	48	43	31
1968 Max.	[illegible]	61	76	67	60	50
Min.	[illegible]	42	46	[illegible]	39	32
5-year average:						
Max.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Min.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[1]Standard deviations averaged 8° F. for maximum and 7° F. for minimum temperatures.

Table 5.--*Average*[1] *duration of maximum air temperatures minus [illegible] at the station on the southwest exposure at the 7,100-foot elevation*

Year	May	June	July	Aug.	Sept.	Oct.
			[illegible]			
1964 Max.	7.1	7.6	[illegible]	5.5	5.8	6.0
Min.	8.2	11.1	4.9	6.4	7.4	6.1
1965 Max.	6.6	6.1	6.3	5.7	7.6	6.0
Min.	8.4	7.8	6.4	7.8	11.4	8.4
1966 Max.	6.3	5.5	5.5	5.2	5.2	6.5
Min.	6.5	7.8	5.3	6.2	7.8	9.6
1967 Max.	5.3	6.5	5.8	5.3	5.6	6.5
Min.	8.4	10.9	6.5	5.5	7.3	9.0
1968 Max.	6.7	7.1	5.8	6.3	6.0	7.3
Min.	9.2	10.2	5.6	9.0	7.7	10.0
5-year average:						
Max.	6.4	6.6	5.9	5.6	6.0	6.5
Min.	8.1	9.6	5.7	7.0	8.3	8.6

[1]Standard deviations averaged 2.7 hours for maximum and 3.9 hours for minimum temperature durations.

Air temperature differences between southwest and northeast exposures were small and somewhat inconsistent. Maximum temperatures averaged 0.4° F. (σ = 1.1)[1] and 1.4° F. (σ = 1.0) higher on the southwest than on the northeast exposures at the 7,100- and 8,200-foot elevations, respectively. Minimum temperatures averaged 0.8° F. (σ = 1.3) lower on the southwest than on the northeast exposure at an elevation of 7,100 feet, but were 0.4° F. (σ = 1.4) lower on the northeast than on the southwest exposure at an elevation of 8,200 feet. The reason for this inconsistency is unknown.

Differences in air temperature extremes were much greater between elevations than between exposures. As expected, both maximum and minimum temperatures at 7,100 feet were higher than those at 8,200 feet. The difference in maximum temperatures was 5.5° F. (σ = 1.6) on southwest exposures, and 6.4° F. (σ = 1.6) on northeast exposures. Minimum temperatures on both exposures were approximately 2.5° F. (σ = 1.8) higher at the lower stations than at the upper stations.

Although the duration of maximum temperatures did not differ between exposures, that of minimum temperatures did. Minimum temperatures lasted 0.3 hour (σ = 1.1) longer on northeast than on the southwest exposures at the lower stations and 1.0 hour (σ = 1.2) longer at the upper stations.

Both maximum and minimum temperatures lasted longer at the upper stations than at the lower stations. This difference was about 0.3 hour (σ = 1.0) for maximum temperatures on both exposures and for minimum temperatures, 1.5 hours (σ = 1.3) on southwest exposures and 2.5 hours (σ = 1.7) on northeast exposures.

Thus, not only did the stations at 8,200 feet have lower minimum temperatures than the stations at 7,100 feet but these minimums lasted much longer as well. Although conspicuously higher maximum temperatures were reached at the 7,100-foot stations, they did not last quite as long as those at the upper stations.

Soil Temperature

Maximum temperatures of the shaded soil surface closely parallel maximum air temperatures, but are a few degrees higher (fig. 5). The monthly means of these maximum temperatures are 3° to 8° F. above those taken in the standard Weather Bureau shelter (tables 4 and 6).

However, maximum surface temperatures of the soil taken in full sunlight are much greater than maximum air temperatures. Monthly means were 23° to 53° F. higher (tables 4 and 7). The greatest difference occurred in late July when the weekly average of maximum soil surface temperatures in the sun reached 135° F. (fig. 5).

Over the 5-year period, the absolute maximum temperature of the unshaded soil surface was 152° F. This was 66° F. higher than the highest air temperature recorded. Temperatures above 135° F. were recorded at one time or another throughout July and August (fig. 5).

Minimum temperatures on the soil surface did not differ nearly as much from air temperatures as the maximums. Monthly means of minimum temperatures of the soil surface taken in the shade were about the same as those of air temperature and those taken on the unshaded soil surface were only 4° to 10° F. lower than minimum air temperatures (tables 4, 6, and 7). Therefore, minimum temperatures of the unshaded surface were

[1]The standard deviation (σ) characterizes the dispersion about the mean of differences in readings between stations.

about 4° to 10° F. lower than those of the shaded surface. The greatest differences between the minimum temperatures of the unshaded soil surface and air temperatures or temperatures of the shaded soil surface were recorded in July and August. Below freezing temperatures on the unshaded soil surfaces can occur anytime during the growing season (fig. 6). For example, a minimum temperature of 20° F. was recorded in early August of 1968. It is not unusual in late July and early August to have a spread of over 115° F. in a 12-hour period between maximum and minimum temperatures on an unshaded soil surface.

Although temperatures on the unshaded surface of the soil were much more extreme than temperatures of the air, the durations of these extremes were shorter (table 8). Temperatures stayed within 5° F. of the maximum for an average of 1.7 to 3.4 hours, less than half as long as those of the air. Temperatures of the unshaded surface stayed within 5° F. of their minimum for a monthly average of 4.6 to 8.8 hours/day. This was about three-fourths as long as air temperatures remained within 5° F. of their minimum during June through August and about equal to durations of minimum air temperatures during May, September, and October.

Unshaded surfaces on southwest exposures reached higher maximum temperatures than those on northeast exposures. This difference averaged 4.1° F. (σ = 5.8) at 7,100 feet and 3.0° F. (σ = 6.4) at the 8,200-foot elevation. Maximum temperatures of shaded soil surfaces did not differ appreciably between exposures.

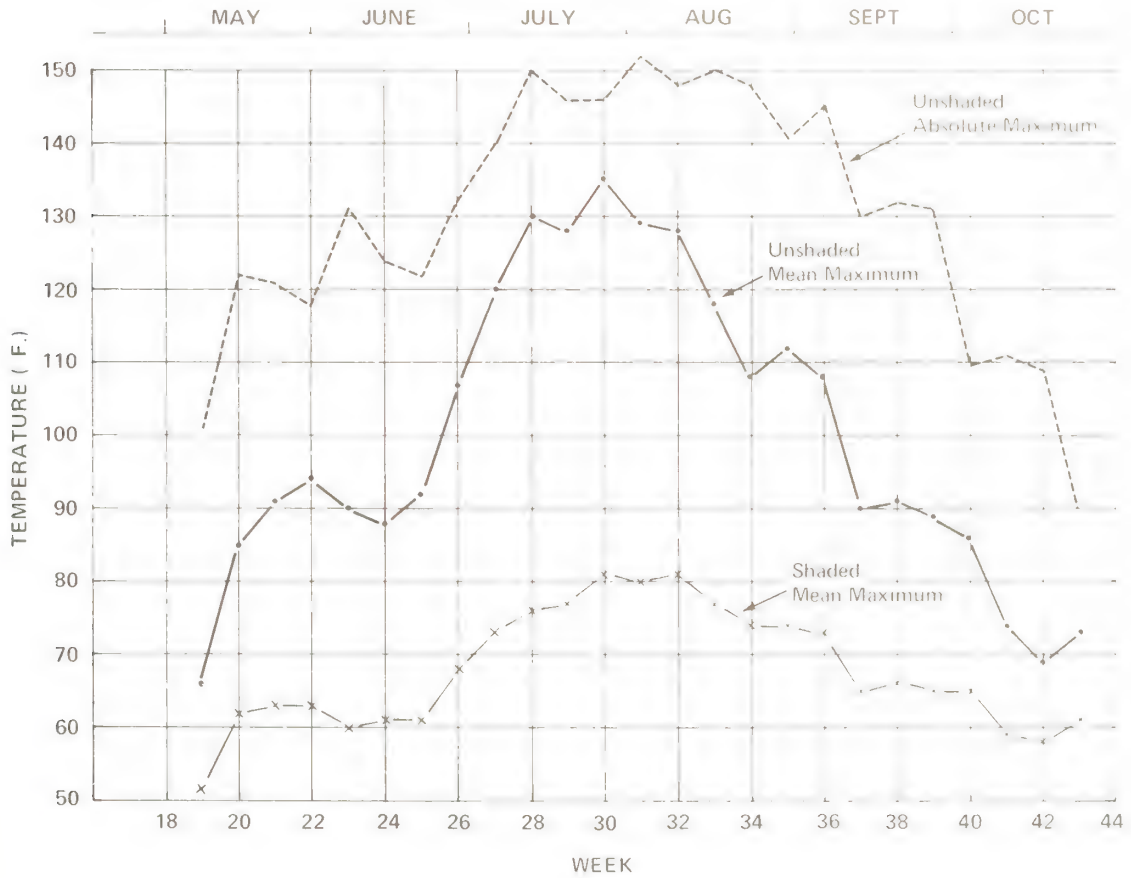

Figure 5.--Maximum temperatures of shaded and unshaded soil on a southwest exposure at 7,100 feet elevation: average weekly means and absolute maximums for the 5-year period.

Table 6.--*Average*[1] *maximum and minimum soil surface temperatures in the shade at the station on the southwest exposure at the 7,100-foot elevation*

Year	May	June	July	Aug.	Sept.	Oct.
			°F.			
1964 Max.	66	65	82	79	73	70
Min.	38	43	47	45	38	33
1965 Max.	54	62	70	72	53	62
Min.	34	41	46	46	36	36
1966 Max.	63	64	80	81	76	62
Min.	36	39	46	43	42	30
1967 Max.	63	62	74	83	75	53
Min.	35	40	47	45	41	32
1968 Max.	55	62	78	71	65	55
Min.	31	39	43	42	37	30
5-year average:						
Max.	60	63	77	77	68	60
Min.	35	40	46	44	39	32

[1]Standard deviations averaged 10° F. for maximum and 6° F. for minimum monthly temperatures.

Table 7.--*Average*[1] *maximum and minimum temperatures of an unshaded soil surface at the station on the southwest exposure at the 7,100-foot elevation*

Year	May	June	July	Aug.	Sept.	Oct.
			°F.			
1964 Max.	102	93	131	114	104	88
Min.	31	38	38	36	32	26
1965 Max.	68	95	115	112	66	80
Min.	30	34	37	37	30	29
1966 Max.	88	106	132	121	106	68
Min.	30	31	36	33	33	25
1967 Max.	83	88	127	141	116	67
Min.	31	35	39	35	33	27
1968 Max.	80	89	131	107	93	71
Min.	28	55	35	35	35	27
5-year average:						
Max.	84	94	127	119	97	75
Min.	30	35	37	35	33	27

[1]Standard deviations averaged 20° F. for maximum and 7° F. for minimum monthly temperatures.

MUEGGLER W. F.

1971. Weather variations on a mountain grassland in southwestern Montana, USDA Forest Serv. Res. Pap. INT-99, 25 p., illus.

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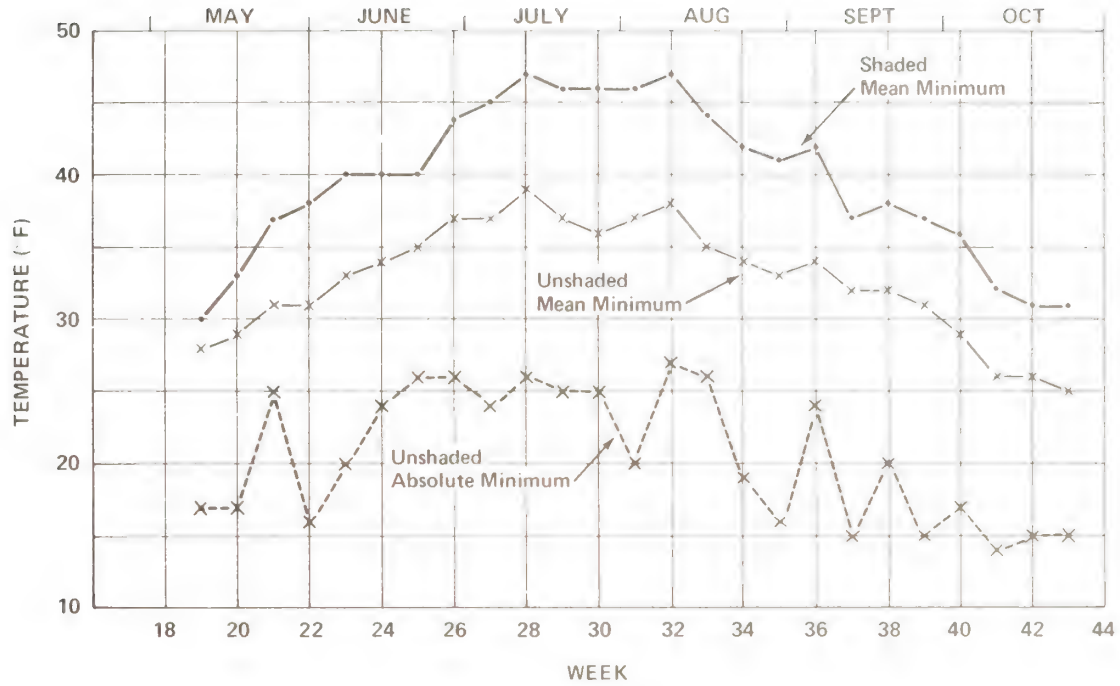


Figure 6.--Minimum temperatures of shaded and unshaded soil surfaces at the station on the southeast exposure at 7,100 feet elevation: average weekly means and absolute minimums for the 5-year period.

Table 8.--*Average*[1] *durations of maximum temperatures minus 5° F. and minimum temperatures plus 5° F. to the nearest soil surface at the station on the southwest exposure at the 7,100-foot elevation*

Year	May	June	July	Aug.	Sept.	Oct.
	- - -

The effects of exposure on minimum temperatures of the soil surface differed with shading. Minimum temperatures of unshaded surfaces were lower on southwest exposures by 0.7° F. (σ = 2.2) at the lower elevation, and by 5.6° F. (σ = 4.0) at the upper elevation. In contrast, minimum temperatures of shaded surfaces were lower on northeast exposures by 1.0° F. (σ = 1.8) at the lower elevation and 1.6° F. (σ = 2.0) at the upper elevation.

The effects of elevation on surface temperature of the soil are more pronounced than those of exposure. Maximum and minimum temperatures were highest at the 7,100-foot elevation with one exception. Inexplicably, the unshaded surface on northeast exposures was colder at the lower station than at the upper. Otherwise, the differences in temperature between elevations are similar on the two exposures. Stations at the 7,100-foot elevation differ from those at 8,200 feet by:

	SOIL SURFACE			
	Shaded		*Unshaded*	
	(°F.)	*(σ)*	*(°F.)*	*(σ)*
Average maximum temperature				
Southwest exposures	8.4	(3.0)	12.4	(6.7)
Northeast exposures	7.9	(3.1)	11.4	(7.5)
Average minimum temperature				
Southwest exposures	4.4	(1.7)	2.9	(2.8)
Northeast exposures	4.7	(2.0)	-2.4	(3.5)

Soil temperature at various depths followed a seasonal curve similar to that of air temperature, but was more subdued (fig. 7). At all three depths (20, 50, and 100 cm.), the average daily temperature in early May was just above freezing. As the growing season progressed the temperature gradually increased, reaching a maximum in late July and early August. The temperature at all depths had dropped to less than 40° F. by the end of October. As was expected, temperature response lagged as soil depth increased. The temperature at the 20-cm. depth peaked in late July and began to drop thereafter. The temperature at the 100-cm. depth peaked about 1 week later but did not decrease more than 1° F. until the first of September--about 1 month after the drop began at the 20-cm. depth.

From May until mid-August, temperatures at a depth of 20 cm. averaged 2° to 4° F. above those at 50-cm. depth. A temperature reversal occurred in late August. From then on, the temperatures at a depth of 50 cm. were as much as 4° F. warmer than those at the 20-cm. depth. Temperatures at the 50-cm. depth remained 2° to 5° F. warmer than those at the 100-cm. depth until about mid-September. The temperature crossover here took place in early October. At that time, the 50-cm. depth became colder than the 100-cm. depth. The year-to-year variation in soil temperature decreased with depth. At all depths, yearly variation was greatest in late summer.

Soil temperatures at all depths differed considerably between exposures and between elevations. Soils on southwest exposures were warmer than those on northeast exposures, and soils at 7,100 feet were warmer than those at 8,200 feet. As was true of air and soil surface temperatures, differences in soil temperatures at all depths were much greater between elevations than between exposures. These differences in soil temperature were:

	SOIL DEPTH					
	cm.		50 cm.		100 cm.	
	(°F.)					
Southwest exposure warmer						
At 7,100 feet by	2.9	(1.8)	3.7	(1.6)	3.3	(1.3)
At 8,200 feet by	2.2	(2.0)	2.3	(1.5)	1.9	(1.2)
Lower elevation warmer						
On southwest exposure by	6.6	(1.7)	7.4	(1.4)	6.8	(1.2)
On northeast exposure by	5.6	(2.1)	5.9	(2.2)	5.3	(2.0)

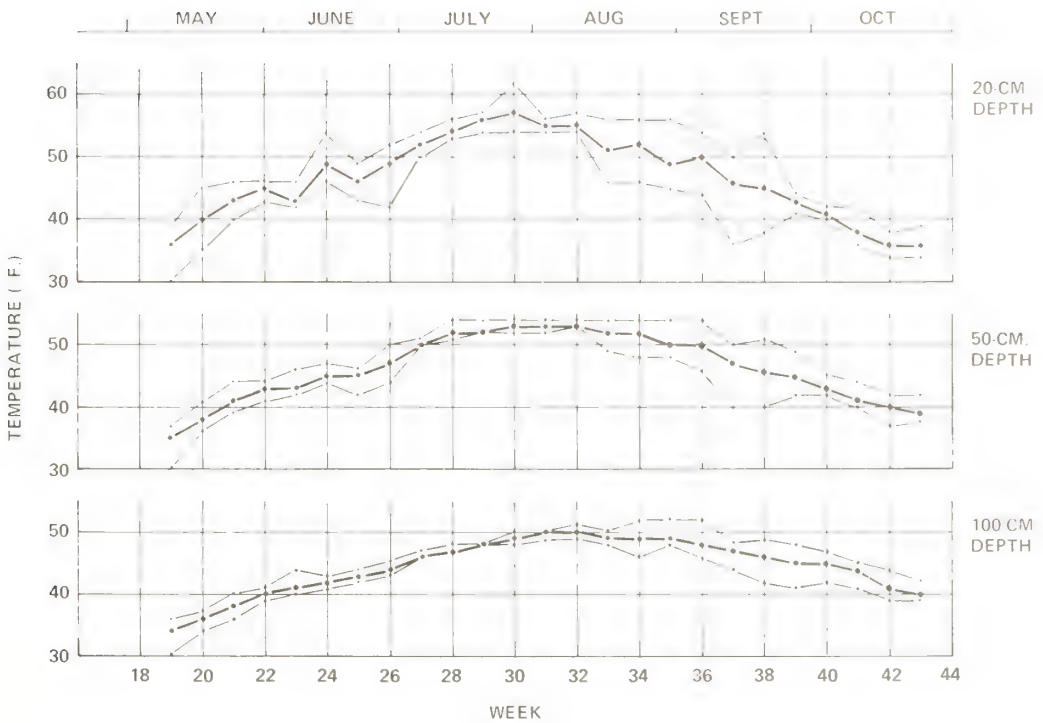


Figure 7.--Soil temperature at three depths at the station on the southwest exposure at 7,100 feet elevation: 5-year average and range.

Relative Humidity

Trends in relative humidity over the growing season were not pronounced. Minimum humidity generally was highest in mid-June and lowest in July and August (fig. 8). Humidity readings for the same time periods varied considerably between years. The yearly variations of minimum humidity were greatest early and late in the season, corresponding to periods of generally unstable weather. During the moist June period, weekly averages of minimum humidity were sometimes greater than 50 percent. Even during the driest part of the summer, weekly averages seldom dropped below 15 percent. Monthly averages of maximum and minimum relative humidity over the 5-year period are given in table 9.

Maximum and minimum humidities remained within 5 percentage units of their daily extremes an average of about 4.5 hours. Maximum and minimum readings were of about the same duration until July and August (table 10). During these 2 months, minimum humidity usually lasted longer than maximum.

Minimum relative humidity averaged less than 2 percent lower on southwest exposures than on northeast exposures. Differences attributable to elevation were somewhat greater. Stations at 7,100 feet were 2.9 percent (σ = 2.8) lower on southwest exposures, and 3.8 percent (σ = 3.2) lower on northeast exposures than the stations at 8,200 feet.

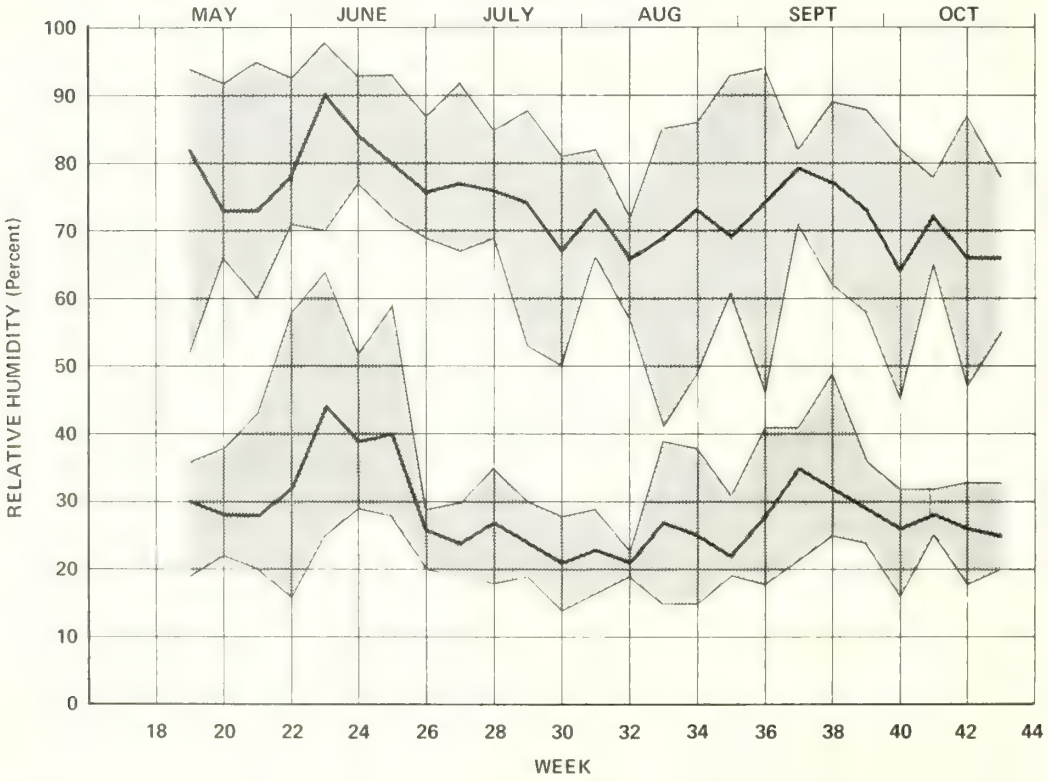


Figure 8.--Relative humidity at the station on the southwest exposure at 7,100 feet elevation: weekly means of daily maximum and of daily minimum humidity; averages and range of means over the 5-year period.

Table 9.--*Daily maximum and minimum relative humidity averaged*[1] *by months at the station on the southwest exposure at the 7,100-foot elevation*

Year	May	June	July	Aug.	Sept.	Oct.
	- - -

Wind

Wind velocities averaged by weeks varied over the 5 years from a low of 2.8 m.p.h. to a high of 10.0 m.p.h. Weekly averages usually remained in the 4.5 to 6.5 m.p.h. range (fig. 9). The only discernible trend was an apparent increase in velocity during October each year.

The southwest exposures were somewhat more windy than the northeast. Velocity differences between exposures averaged 0.3 m.p.h. (σ = 0.9) at the lower elevation and 1.0 m.p.h. (σ = 1.0) at the upper elevation. Greater wind velocity on the southwest exposures may reflect the prevalence of convectional summer storms from the west. Stations on the southwest slope were more directly exposed to these storms than stations on the northeast.

Elevational differences in wind velocity were slightly greater than those of exposure. The stations at 8,200 feet received 1.4 m.p.h. (σ = 1.0) more wind on southwest exposures and 0.7 m.p.h. (σ = 0.8) more wind on northeast exposures than did the stations at 7,100 feet.

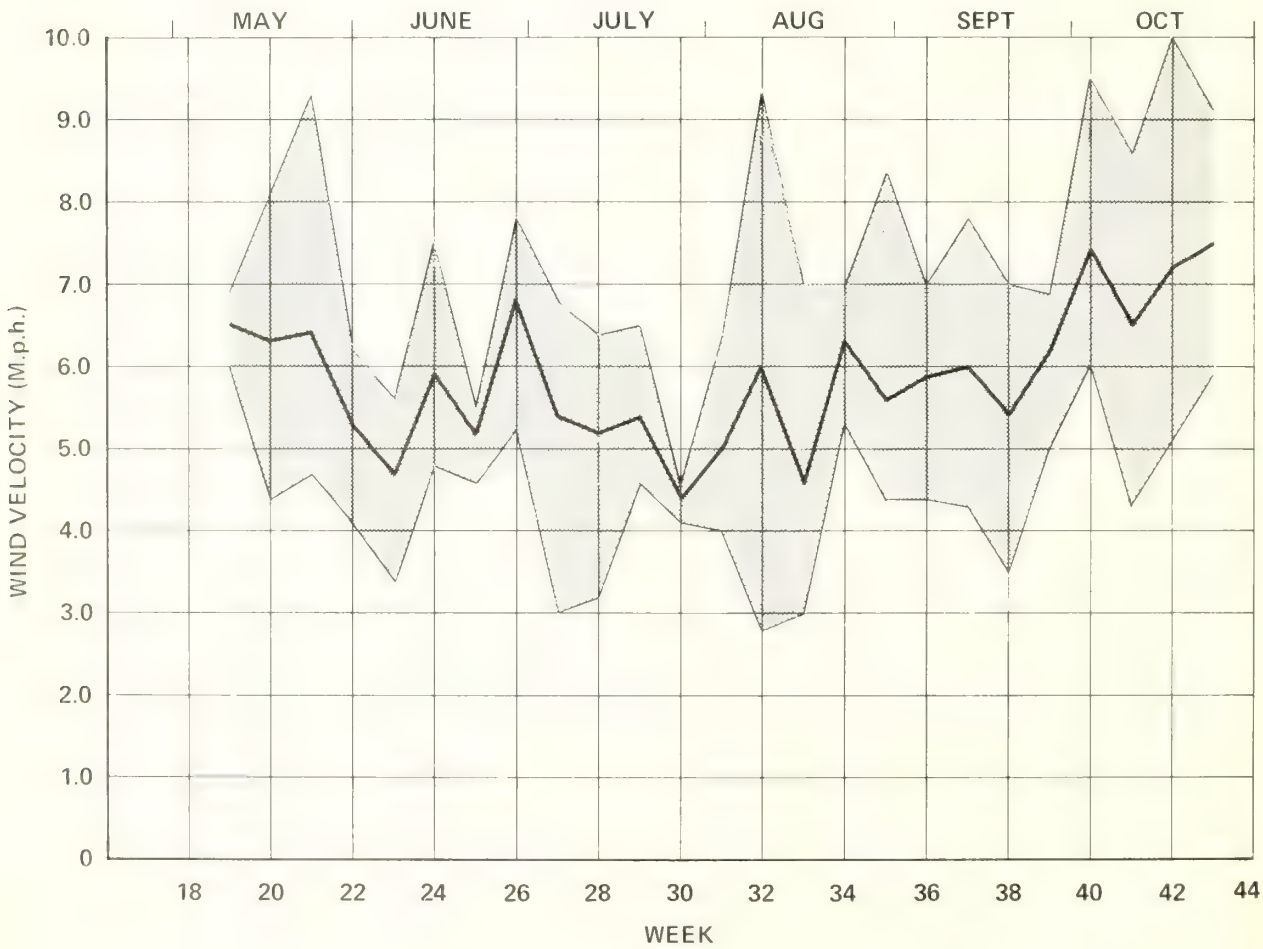


Figure 9.--Wind velocity at the station on the southwest exposure at 7,100 feet elevation: 5-year average of weekly means and range of weekly means.

Precipitation

Over the 5 study years, precipitation for the months May-October varied from 7.18 to 12.24 inches (table 11). Usually over 50 percent of the total precipitation during any growing season arrived in May and June, primarily the latter and sometimes as snow. Precipitation diminished abruptly in July (fig. 10). Both July and early August were relatively dry. After the middle of August, precipitation would usually increase again. Snow was fairly common in the late August and September storms, but it would melt within a few days. Precipitation ordinarily diminished again by late October.

On an average, measurable precipitation occurred on 27 percent of the days from May through October. Usually, June had by far the greatest number of rainy days, although September occasionally had at least as many. Over the 5-year period, as many as 20 precipitation days occurred in June and as few as two in July, two in August, and one in September (table 11). The 20 days of precipitation in June, 1967 yielded 4.81 inches, a maximum monthly total for the 5-year period.

No difference in amount of precipitation was observed between exposures, but some difference was recorded between elevations. Stations at 8,200 feet received 0.11 inch per week ($\sigma = 0.26$) more precipitation than the stations at 7,100 feet, or 2.75 inches more precipitation over a 6-month period.

Table 11.--*Total monthly precipitation and average number of precipitation days per month over a 5-year period at the station on the southwest exposure at the 7,100-foot elevation*

Year		May	June	July	Aug.	Sept.	Oct.	Total
1964	Precip.	[1]--	3.83	0.67	0.89	0.05	0.70	8.31
	Days	--	16	4	4	1	3	
1965	Precip.	2.96	2.90	1.59	1.96	2.16	.67	12.24
	Days	9	14	8	10	15	5	
1966	Precip.	1.68	2.45	.39	.55	1.68	.43	7.18
	Days	8	12	5	5	5	4	
1967	Precip.	[1]--	4.81	2.05	.18	.67	1.93	11.81
	Days	--	20	9	2	4	14	
1968	Precip.	1.87	4.14	.15	1.87	2.23	.92	11.18
	Days	12	13	2	11	12	6	
5-year average:								
	Precip.	2.17	3.62	.97	1.09	1.36	.93	10.14
	Days	10	15	6	6	7	6	50

[1]Data not available for entire month; estimated as 2.17 for computation of totals.

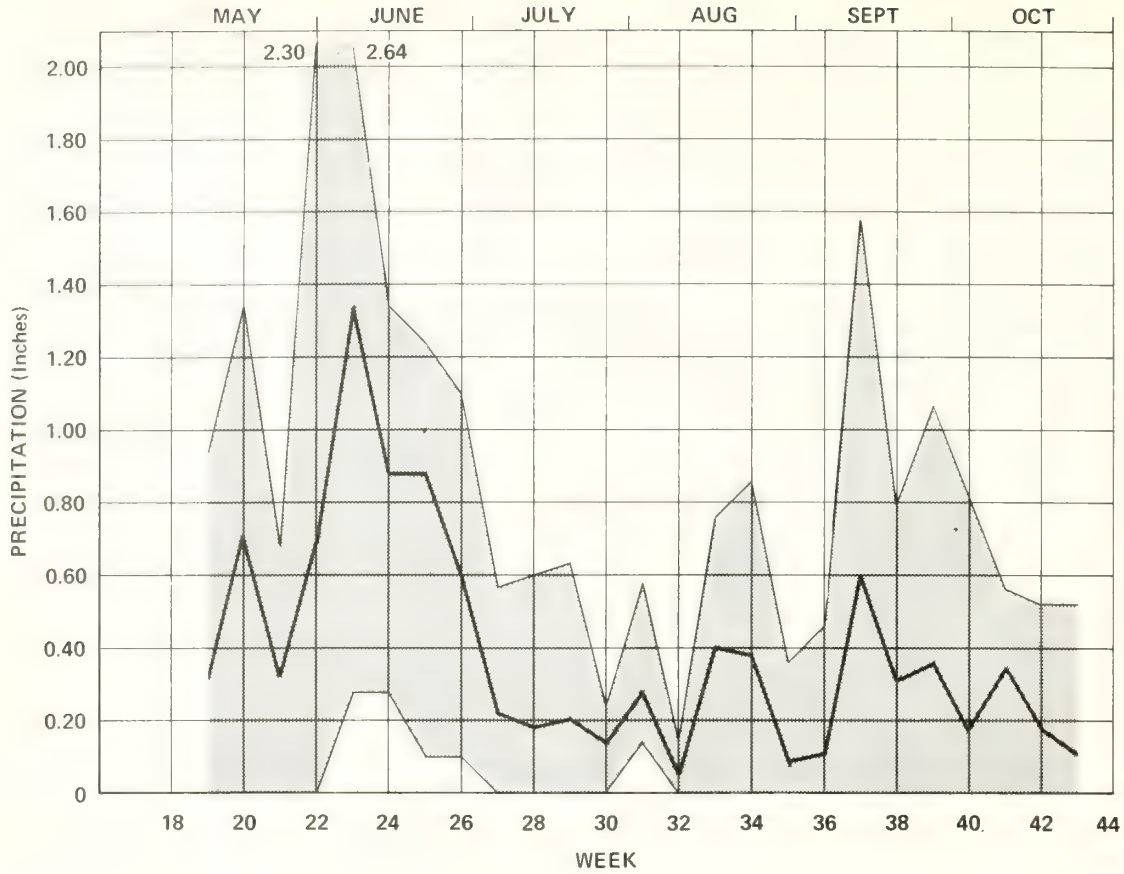
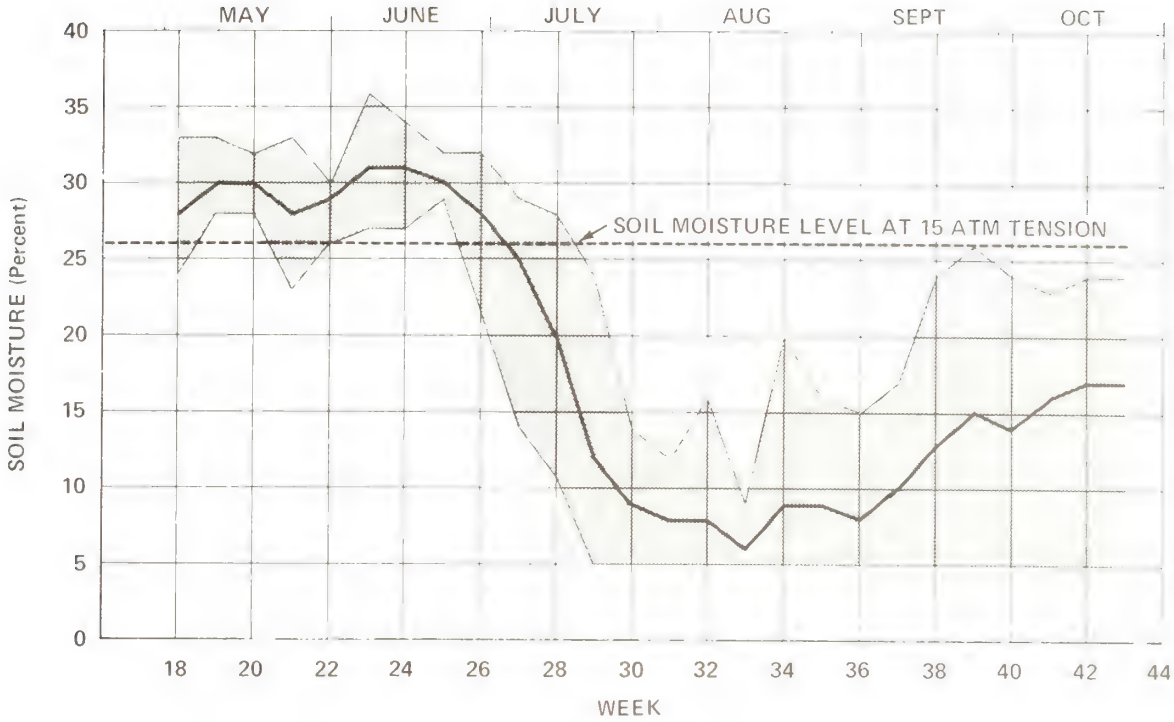


Figure 10.--Precipitation at the station on the southwest exposure at 7,100 feet elevation: 5-year average and range of weekly totals.

Soil Moisture

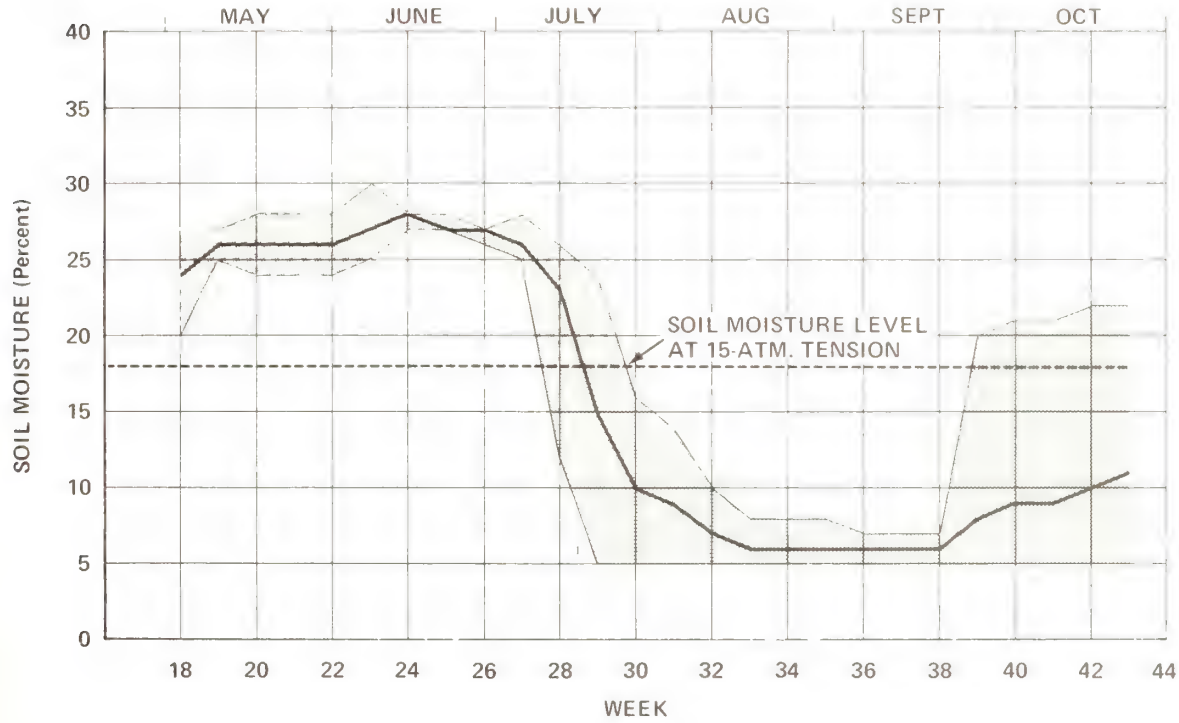
Average seasonal trends in the soil's moisture content at 20-, 50-, and 100-cm. depths are shown in figures 11-13. These trends should be viewed with respect to moisture stress for plants primarily. The 15-atm. moisture-tension level indicated on each figure is considered the point at which moisture availability generally starts to limit plant growth. The position of this level depends largely upon soil texture; consequently, it often differs with soil depth. Monthly averages of soil moisture are shown in table 12.

Moisture levels at the 20- and 50-cm. depths were usually near maximum at the beginning of the growing season, early in May. The moisture level at 100-cm. depth was also near maximum on the northeast exposure. However, May and June rains were required to replenish the moisture supply at the 100-cm. depth on the southwest exposure. The snowpack on southwest exposures is typically shallower than that on the northeast exposures; consequently, less moisture is available to recharge the soil mantle on the southwest exposure.



[1] Electrical resistance readings in excess of 1 million ohms arbitrarily assigned soil moisture value of 5%.

Figure 11.--Soil moisture at the station on the southwest exposure at 7,100 feet elevation: 5-year average and range of weekly readings at 20-cm. depth.



[1] Electrical resistance readings in excess of 1 million ohms arbitrarily assigned soil moisture value of 5%.

Figure 12.--Soil moisture at the station on the southwest exposure at 7,100 feet elevation: 5-year average and range of weekly readings at the 50-cm. depth.

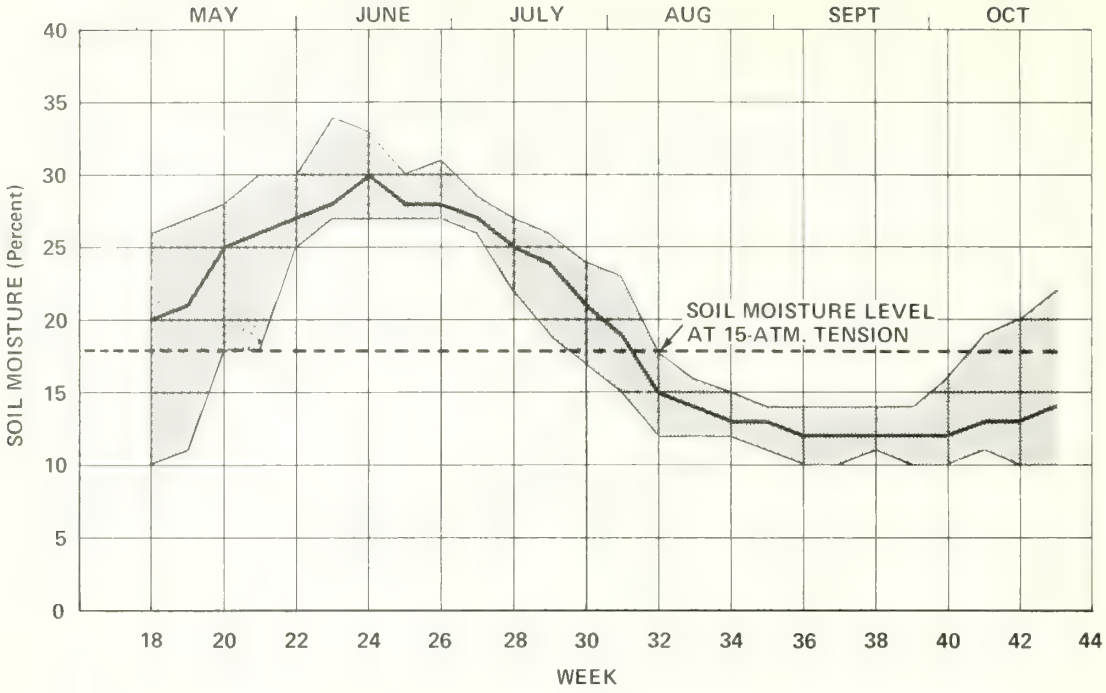


Figure 13.--Soil moisture at the station on the southwest exposure at 7,100 feet elevation: 5-year average and range of weekly readings at the 100-cm. depth.

Table 13.--[illegible] on the station on the southwest exposure at the 7,100-foot elevation

Year	Depth	May	June	July	Aug.	Sept.	Oct.	Wilting point[1]
				Percent by weight				
1964	20 cm.	26	30	10	[illegible]	5	5	26
	50 cm.	24	26	13	5	5	5	18
	100 cm.	24	28	25	14	11	11	18
1965	20 cm.	29	28	21	10	15	24	26
	50 cm.	25	27	24	[illegible]	9	21	18
	100 cm.	22	26	27	18	14	19	18
1966	20 cm.	32	28	10	5	12	14	26
	50 cm.	27	27	13	5	5	5	18
	100 cm.	26	25	22	13	11	12	18
1967	20 cm.	27	32	23	9	5	14	26
	50 cm.	26	27	25	[illegible]	5	5	18
	100 cm.	16	27	26	16	11	10	18
1968	20 cm.	29	32	19	11	17	23	26
	50 cm.	27	30	18	7	7	12	18
	100 cm.	27	31	23	14	14	14	18
5-year average.								
	20 cm.	29	30	17	8	11	16	26
	50 cm.	26	27	18	[illegible]	6	10	18
	100 cm.	25	27	24	15	12	13	18

[1]Determined by pressure membrane at 15-atm.
[2]Electrical resistance in excess of 1 million ohms, arbitrarily assigned 5 percent soil moisture.

The drop in soil moisture content usually began in late June at the 20-cm. depth, and in early July at the 50- and 100-cm. depths. Moisture at a depth of 20 cm. usually started to become limiting for plant growth in early July, but the time at which this limiting point was reached varied by about 3 weeks over the 5-year period. Moisture did not become limiting at the 50-cm. depth until mid- to late July or at the 100-cm. depth until early August. The time that the limiting point was reached at these depths varied over the study years by approximately 2 weeks.

Recharge of moisture levels in the upper soil mantle began with the August and September storms. The great variability in occurrence and intensity of these storms between years results in an equally great variability of soil moisture recharge. Recharge at the 100-cm. depth did not ordinarily begin until October. By the end of October the amount of recharge at all levels did not usually exceed that held at 15-atm. tension.

There were no consistent differences in moisture depletion at the 20-cm. depth on different exposures. However, at depths of 50- and 100-cm., the moisture depletion curves crossed below the 15-atm. level about a week earlier on southwest exposures than they did on northeast exposures. At 7,100 feet, soil moisture became limiting at all depths sooner than at 8,200 feet. The moisture curves for the lower stations crossed below the 15-atm. level about 1 week earlier at the 20-cm. depth and about 2 weeks earlier at the 50- and 100-cm. depths than those for the upper stations. These differences in time of soil moisture depletion were reflected in the vegetation. Plants dried sooner on southerly exposures than on northerly and sooner at 7,100 feet than at 8,200 feet.

Comparisons With Weather Bureau Stations

U.S. Dep. of Commerce Weather Bureau records of temperature and precipitation collected from the two nearest official stations were compared with those obtained in this study from the station on the southwest exposure at 7,100 feet. The nearest Weather Bureau station was 12 miles northwest in Virginia City, Montana, at an elevation of 5,835 feet. The other Weather Bureau station, Ennis, Montana, was 14 miles north-northeast at an elevation of 4,953 feet. Both of these stations are in mountain valleys. Virginia City is in a rather narrow valley virtually enclosed by mountains. Ennis is in the much broader Madison River Valley; the closest mountains are several miles away.

Maximum temperatures, both average and absolute, were approximately 8° F. higher at Virginia City and 10° F. higher at Ennis than at the station at 7,100 feet (table 13). The maximum temperature difference between the station at 7,100 feet and that at Virginia City represents a decrease of about 6.3° F. per 1,000-foot rise in elevation. Comparison of records at the station at 7,100 feet with those at Ennis shows a decrease of about 4.7° F. per 1,000-foot elevation rise. This is fairly comparable to the 5.4° F. decrease per 1,000-foot elevation rise between the stations at 7,100 and 8,200 feet.

Differences of minimum temperatures were much smaller than those of maximum temperatures (table 13). Minimums at Virginia City averaged about 3° F. warmer and at Ennis about 2.5° F. warmer than those at the station at 7,100 feet. The respective decreases amounted to 2.4° F. and 1.2° F. per 1,000-foot elevation rise, compared to a 2.5° F. decrease per 1,000-foot rise between the grassland stations at 7,100 and 8,200 feet. Topographic differences between Virginia City and Ennis probably account for the latter having a slightly colder minimum in spite of being about 900 feet lower in elevation.

Differences in precipitation between the station at 7,100 feet and those at Virginia City and Ennis were not consistent with elevational differences (table 13). Average monthly precipitation from May through October was 0.25 inch lower at Ennis and 0.31 inch higher at Virginia City than that recorded at 7,100 feet. Both the station at 7,100 feet and Ennis are on the east side of the Gravelly Range, whereas Virginia City lies west of the divide. Thus, Virginia City is in a better position to receive rains from summer storms that commonly approach from the west.

These comparisons illustrate the error possible in attempting to project data even on averages obtained from nearby valley stations to mountain slopes. Depending on which of the two valley stations is used, the adjustment for maximum temperatures would be a 4.7° F. or 6.3° F. decrease per 1,000-foot rise and for minimum temperatures a 1.2° F. or 2.4° F. decrease per 1,000-foot rise. This compares favorably to the average differences of 5.4° F. for maximum and 2.5° F. for minimum temperature decrease per 1,000-foot elevation rise measured on the mountain grasslands themselves. However, the projection of precipitation data is subject to much greater error; depending upon the valley station selected, the adjustment would be a decrease of 0.24 inch/month per 1,000-foot rise or an increase of 0.12 inch/month per 1,000-foot rise in elevation. The precipitation difference resulting from elevational differences between the mountain grassland stations amounted to an increase of 0.42 inch/month per 1,000-foot rise in elevation.

Table 13.--*Average weather differences between the 7,100-foot station on the southwest exposure and records*[1] *obtained at Virginia City, Mont., and Ennis, Mont.*

	VIRGINIA CITY (5,835-foot elevation)	ENNIS (4,953-foot elevation)
	Differ from 7,100-foot station by:	
TEMPERATURE (°F.)	(σ)	(σ)
Mean monthly maximum	8.1 (1.6)	10.4 (1.7)
Absolute monthly maximum	7.8 (2.3)	10.6 (2.3)
Mean monthly minimum	3.3 (3.6)	2.2 (4.7)
Absolute monthly minimum	2.8 (3.7)	2.7 (2.9)
PRECIPITATION		
(Inches/Month)	0.31 (0.76)	-0.25 (0.77)

[1]U.S. Dep. Commerce, Weather Bureau climatological data, monthly summaries.

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USDA Forest Service
Research Paper INT-100

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The authors wish to thank Chester E. Jensen, mathematical statistician, of the Intermountain Forest and Range Experiment Station, Ogden, Utah, for his generous assistance with the development of the statistical models presented in this paper.

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ABSTRACT

This was a laboratory study of soil erosion, performed on bare soil plots under simulated rainfall. The variables having the greatest effect on erosion by overland flow were rainfall intensity, slope steepness, and the percentage by weight of soil particles greater than 2 mm. The variables having the greatest influence on raindrop splash erosion were rainfall intensity, slope steepness, percentage by weight of soil particles between 60 and 2,000 microns, and soil bulk density.

Introduction

All soils erode to some degree. The rate and severity of erosional losses are primarily controlled by four classes of variables--vegetal factors, soil factors, precipitation factors, and topographic factors. Smith and Wischmeier (1962) cite vegetal cover as the greatest deterrent to soil erosion. Once the cover has been reduced below some critical level, detachment and transport of soil function together to remove the soil mantle, but at varying rates that depend upon both soil and nonsoil factors.

A voluminous amount of literature exists on soil erosion from forest and range lands. A large portion of this literature has been concerned with soil factors and their effects on erosion. Bryan (1968) worked with 22 indices of soil erodibility that have been reported in the literature. He concluded that none of the soil indices was reliable in operation and capable of universal application. He expressed doubt that such an index could be developed, but concluded that the percentage weight of water-stable aggregates greater than 3 mm. in diameter was probably the most reliable index of soil erodibility available.

Many important questions concerning the influence of soil factors on erosion processes remain unanswered. This situation is partially due to the fact that soil factors are difficult to isolate in the presence of vegetal factors. Another difficulty has been the multiplicity of soil erosion criteria. Weight of eroded soil, numerous measures of soil aggregation, stream turbidity, measurements from various types of erosion gages, and several soil indices have all been used as erosion criteria.

In addition to vegetal cover and soil variables, the dominant factors controlling erosion are rainfall characteristics and topography. However, on forest and range lands, the effect of these two factors is not well known. Most of our information concerning rainfall factors and topographic factors has been obtained from studies on farmlands.

Wischmeier and Smith (1958) demonstrated the importance of rainfall energy to soil loss from agricultural lands. However, information on the kinetic energy of rainfall is totally absent for mountainous areas. Wischmeier (1959) and others have implied that the relationship between rainfall intensity and kinetic energy is acceptably constant in agricultural regions. No such relationship should be expected in mountainous areas of the Intermountain Region because these areas are subject to rainstorms that vary widely in those characteristics directly affecting rainfall energy; i.e., distributions of drop sizes, rainfall intensity, and wind velocities.

For most point measures of soil erosion at a given time, the precipitation factors of greatest interest are rainfall intensity, raindrop-size distribution, and total rainfall. If our interests in soil erosion expand in either time or space, the information needed must include rainfall frequency-intensity-duration relations, and depth-area-duration relations. In mountainous areas, such data are scanty.

The topographic factors of major importance to soil erosion in mountainous terrain are slope steepness and slope length. Sometimes aspect and elevation appear to be related to soil losses; although these are probably indirect effects that reflect differences in climate or vegetation, rather than topographic effects. Naturally, large variations in both slope steepness and slope length occur in mountainous areas. There is some evidence that the effects of slope length and steepness on soil erosion are interrelated with other factors, such as soil texture, soil bulk density, vegetal type, or rainfall intensity. However, most of our practical information on the effects of slope steepness has come from basic kinematic theory; e.g., the velocity of overland

Table 1.--*Results of mechanical analyses showing the average percent gravel, sand, silt, and clay for soils used in this study*

Soil	Percent >2,000μ*	Percent 2,000-61μ	Percent 61μ-2μ	Percent <2μ
Low-elevation granitic	23	56	15	6
High-elevation granitic	36	46	12	6
Wasatch clay	0	21	28	51

*One micron equals 0.001 mm.

flow varies as the square root of the slope gradient and the energy of overland flow varies as the square of its velocity. Overland flow will move down a 40-percent slope at twice the velocity of that on a 10-percent slope. By doubling the velocity, the energy of flow will increase about four times; the size of particle that can be transported will be increased about 64 times (sixth power of velocity); and the quantity of material of a given size that can be carried is increased about 32 times (fifth power of velocity).

In this paper we summarize the results of laboratory soil erosion tests performed on bare soil plots under simulated rainfall. The effects of soil, precipitation, and topographic factors were examined. Vegetation was not included because the influence of nonvegetal factors on erosion is more difficult to isolate in the presence of vegetal cover. Moreover, problem areas that exhibit high rates of soil erosion and stream sedimentation are often nearly devoid of vegetal cover. Low cover densities may result from a variety of causes; fire, logging, road construction, and grazing have been common ones in the past.

This work was intended to develop information about the effects of soil, slope, and rainfall variables on the erodibility of bare soil, to determine the magnitude of these effects, and to identify relationships between these variables.

Methods and Materials

Three soils were used in this study. Two of these, formed on weathered granitic rock, were collected in Idaho on the Boise National Forest, one at about 3,900 feet m.s.l., the other at about 7,800 feet m.s.l. The third soil, formed over limestone parent material, was collected in central Utah on the Wasatch Plateau, Manti-LaSal National Forest, at about 10,100 feet m.s.l. Only the surface inch of soil was collected. A mechanical analysis was performed on each of these soils (table 1).

These soils were each sieved through a 6.3 mm. screen and loaded in a plot to a depth of about 4 inches. Less than 2 percent of the soil would not pass through this screen. The plot was $48\frac{1}{8}$ by $18\frac{1}{8}$ inches and contained no vegetation. Adequate drainage was provided from the bottom of the plot. After loading the soil, the plot was set to a specified slope ($2\frac{1}{2}$, 18, or 32 percent) so that the long axis of the plot pointed downhill. Average bulk-density after loading the disturbed soil was 1.14 g. per cm.^{3} The soil was wetted to saturation by a mist spray, covered with a plastic sheet, and allowed to drain for 20 hours. Next, constant rainfall of approximately 3 or 7 inches per hour was applied to the soil plot for 30 minutes. The actual rainfall intensity was measured during each run. The rainfall simulator used was the same as that described by Packer (1957), except that the F-type nozzles were raised to

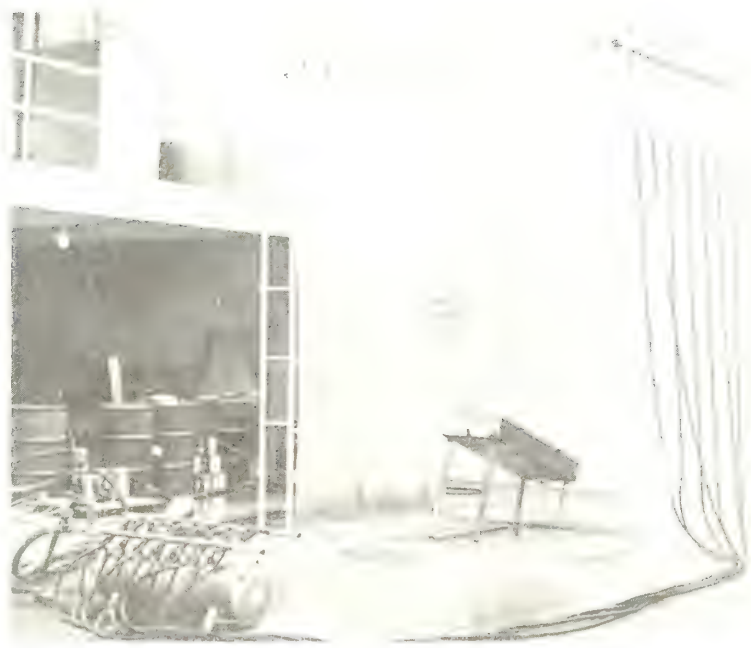

Figure 1.--Rainfall simulator in operation. The plot is inclined to approximately 32 percent slope. Each of the interlocking splash trays on the floor is 9 inches wide. The nozzle rack is 12 feet above the floor.

12 feet above the concrete floor and the hole in the end disc of each nozzle was reduced from 0.125 to 0.104 inch (fig. 1). These modifications greatly increased the fall distance of the drops and reduced the average drop size. The range of drop sizes for both the 3- and 7-inch per hour rainfall intensities varied from less than 0.5 mm. to slightly more than 5.0 mm. At 7 inches per hour intensity, the average drop size was 1.87 mm. and the D_{50} drop size,[1] 3.55 mm. For the 3-inch-per-hour intensity, the average drop size was 1.91 mm. and the D_{50} size, 3.09 mm.

All surface runoff of both water and soil particles was collected and weighed continuously throughout each run. One-pint runoff samples were collected periodically during each run to determine the concentration of soil material in the runoff.

Soil splash was collected all around the perimeter of the plot. Four concentric interlocking trays, each of which was 9 inches wide, were placed around each side and the upper end of the plot. Soil splash at the foot of the plot was collected in one large, unsegmented pan (fig. 1).

After each 30-minute run, a new plot was prepared. In all, 18 runs were made using three soil types, each on three different slopes at two rainfall intensities.

The size distribution for both particles and water-stable aggregates was determined for all soil samples by using a wash bottle to gently wash the soil sample through a set of nested 3-inch sieves.

We desired to use a single parameter to express the aggregate- and particle-size distributions. Since erosion is basically a work process, the size distribution

[1]The D_{50} drop size is that size at which 50 percent of the water comes in drop sizes larger than the D_{50} and 50 percent in drop sizes smaller than the D_{50}.

parameter should be weighted more heavily by large-size fractions than by small-size fractions. This was accomplished by using the mean weight-diameter (Van Bavel 1949).

$$MWD = \sum_{i=1}^{n} \bar{X}i \; Wi$$

where $\bar{X}i$ = mean diameter of each size fraction in millimeters.

Wi = proportion of the total sample weight in the corresponding size fraction.

In addition to the mean weight-diameter, the percent of particles and water-stable aggregates greater than 2 mm. was measured.

Results

SOIL EROSION BY OVERLAND FLOW

Cursory examination of table 1 reveals that the texture of the Wasatch clay soil is very different from the two granitic soils. However, on the basis of preliminary testing the effects of the soil variables appeared to be consistent across soil types. Therefore, the results from all test runs on the three soils were grouped together for regression analysis. A total of 18 test runs (three soils on three degrees of slope steepness at two rainfall intensities) were analyzed.

The weight of soil material washed off the plot was used as the dependent variable in regression analysis. Several soil and nonsoil factors were used as independent variables. The interaction model illustrated in figure 2 explains over 96 percent of

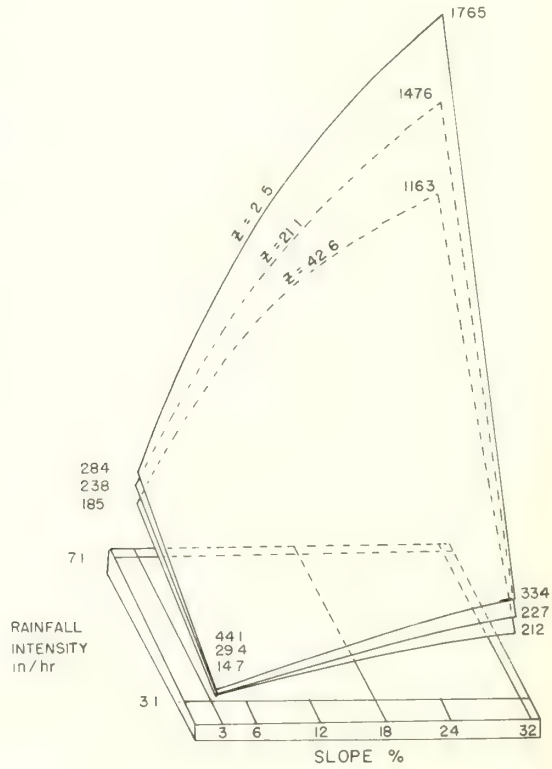

Figure 2.--The relationship between soil erosion by overland flow, rainfall intensity, slope steepness, and the proportion, z, of soil particles and aggregates greater than 2 mm. Each of the three regression surfaces represents a different z value. The numbers at the corners of each surface represent the amount of soil erosion in grams (r^2=0.96).

the variance in soil erosion by overland flow (r^2=0.963). This model clearly shows the effect of the interaction between slope steepness and rainfall intensity on erosion by overland flow. The amount of soil that is eroded by overland flow is relatively small when either slope steepness or rainfall intensity is minimized, but it increases more than five times when both slope steepness and rainfall intensity are maximized. The effect of this interaction is modified by the percent of particles and water-stable aggregates greater than 2 mm. As the proportion of particles and water-stable aggregates greater than 2 mm. increases, the soil erosion amounts decrease. Each of the regression surfaces illustrated in figure 2 represents a specified proportion of soil material greater than 2 mm. (i.e., 2.5, 21.1, or 42.6 percent).

The magnitude of deviations of the observed data from regression varied with values of the independent variables. For convenience in summarizing this information, observations were divided into two groups. Group 1 includes observations on 18- and 32-percent slopes and at high-rainfall intensity. Group 2 includes observations on the $2\frac{1}{2}$-percent slope at high-rainfall intensity and on all slopes at low-rainfall intensity. The average and maximum absolute deviations from regression in group 1 were 158.1 and 264.1 g., respectively. Mean soil erosion for group 1 was 1262.3 g. In group 2, the average and maximum absolute deviations were 24.8 and 66.2 g., respectively; the mean was 190.2 g.

Average deviation is 13 percent of the mean for both groups. These deviations are well within acceptable limits.

To examine the effects of the slope steepness-rainfall intensity interaction without any soil effect, the percent of particles and water-stable aggregates greater than 2 mm. was removed from the regression model (fig. 2). The resulting r^2 was 0.901, compared to an r^2 of 0.963 for the complete model. Therefore, the proportion of soil material greater than 2 mm. explains an added 6 percent of the variance associated with soil erosion by overland flow. But since slope and rainfall intensity account for 90 percent of the variance in soil amounts eroded by overland flow, only 10 percent could be accounted for by added variables. Under these test conditions, the soil factors are much less important than rainfall intensity and slope steepness.

Six soil variables were measured for each of these tests: (1) the percent of particles and water-stable aggregates greater than 2 mm., (2) the percent of particles less than 61 microns as determined by wet-sieve analysis, (3) total silt plus clay divided by the mean weight-diameter (Kemper and Chepil 1965), (4) the percent of particles and water-stable aggregates between 0.061 - 2.0 mm., (5) bulk-density, and (6) the mean weight-diameter. Variables (1) and (6) were highly correlated, r^2=0.996. Since variable (1) was slightly more sensitive than (6) and easier to obtain, the mean weight-diameter, (6), was not used.

The first five soil variables mentioned above were used in a multiple regression analysis with soil eroded by overland flow as the dependent variable. No additive combination of variables nor their transformations were found that explained more than 27 percent of the variance in soil amounts eroded by overland flow. To examine the relative strength of individual soil variables, several models were used. All of these models involved the slope-rainfall intensity interaction and a single soil variable. These models indicated that the percent of particles and aggregates between 61 and 2,000 microns and the percent of particles and aggregates greater than 2 mm. are the most important soil variables affecting soil erosion by overland flow. This result agrees in general with the findings of several other studies made on forest or range soils (Wooldridge 1965; Packer 1967; Ellison 1945).

The mean particle size of the soil that was removed from the plot by overland flow was consistently smaller than the mean particle size of the original soil. Based on the MWD for all samples, the mean particle size of the original soil was 0.945 mm., that of the runoff samples was 0.620 mm., a 38-percent reduction.

SOIL SPLASH

Splash erosion is the initial phase of the water erosion process. For the most part, raindrops provide the detaching force prerequisite for transporting soil particles by the sheet of surface detention water. Even on level areas where net erosion is small (especially on bare soils) as much as 60 tons of soil per acre per hour may be detached and splashed into the air. As slope steepness increases, discharge and velocity of surface water also increases and, correlatively, the rate of soil removal.

Soil splash is not difficult to measure in a laboratory study, but it is difficult to interpret the results of such measurements. In plot studies, soil that is splashed off the plot is "lost"; it is not subject to resplash or to further movement by the sheet of surface detention water. In the field, soil splash is not "lost," but remains available for further movement by splash or transport by the sheet of surface detention water. No satisfactory method has been developed to handle this problem.

On any inclined soil mass subject to raindrop impact, only a portion of the total splash goes in a downhill direction; the balance is splashed laterally or uphill. Neglecting wind effects, the proportion of downhill splash to total splash is largely a function of the slope angle. Downhill raindrop splash and slope angle are directly related, up to some critical slope angle. At that angle, virtually all splashed soil goes downhill.

The downhill component of raindrop splash erosion was not measured directly in this study. The four sidepans on each side of the soil plot contained both the downhill and uphill components of raindrop splash. However, the pan at the bottom of the plot did contain only that soil material that was splashed in a downhill direction. But, the amount of soil splashed into the bottom pan was less than the total downhill splash because some downhill splash was caught in the sidepans.

On the assumption that the same factors affect both bottom pan catch and total downhill raindrop splash, the amount of soil material splashed into the bottom pan was analyzed by regression methods. The weight of soil material splashed into the bottom pan by raindrop action was used as the dependent variable. Rainfall intensity, slope steepness, soil bulk density, and the percent of soil particles and water-stable aggregates between 61 and 2,000 microns (sand-size soil material) were used as independent variables. The regression model, illustrated in figures 3A and 3B, explains nearly 97 percent of the variance associated with splashed soil material that was caught in the bottom pan (R^2=0.966).

Figures 3A and 3B show the effect of the strong interaction between slope steepness and rainfall intensity on raindrop splash erosion. Note that raindrop-splash erosion is quite small on the most shallow slope, even at the greatest rainfall intensity. This does not mean that less soil was splashed on the shallow slope, but that less soil was splashed and transported downhill on the shallow slope. Maximum amounts of soil are eroded by raindrop splash where slope steepness and rainfall intensity are greatest. Pretreatment soil bulk density and the amount of soil-splash erosion are directly related. However, the effect of bulk density on soil splash is more pronounced as slope steepness increases; i.e., at a rainfall intensity of 3.1 inches per hour, the difference in the weights of soil splash between bulk densities of 0.95 and 1.37 g. per cm.^{3} is only 10 g. at 3 percent slope, but 289 g. at 32 percent slope (fig. 3A). Each of the three regression surfaces in figures 3A and 3B represent a different value of pretreatment soil bulk density, namely, 0.95, 1.16, or 1.37 g. per cm.^{3} The effect of

FARMER EUGENE E. and VAN HAVEREN BRUCE P.

1971. Soil erosion by overland flow and raindrop splash on three mountain soils. USDA Forest Serv. Res. Pap. INT-100, 14 p., illus.

This was a laboratory study of soil erosion, performed on bare soil plots under simulated rainfall. The variables having the greatest effect on erosion by overland flow were rainfall intensity, slope steepness, and the percentage by weight of soil particles greater than 2 mm. The variables having the greatest influence on raindrop splash erosion were rainfall intensity, slope steepness, percentage by weight of soil particles between 60 and 2,000 microns, and soil bulk density.

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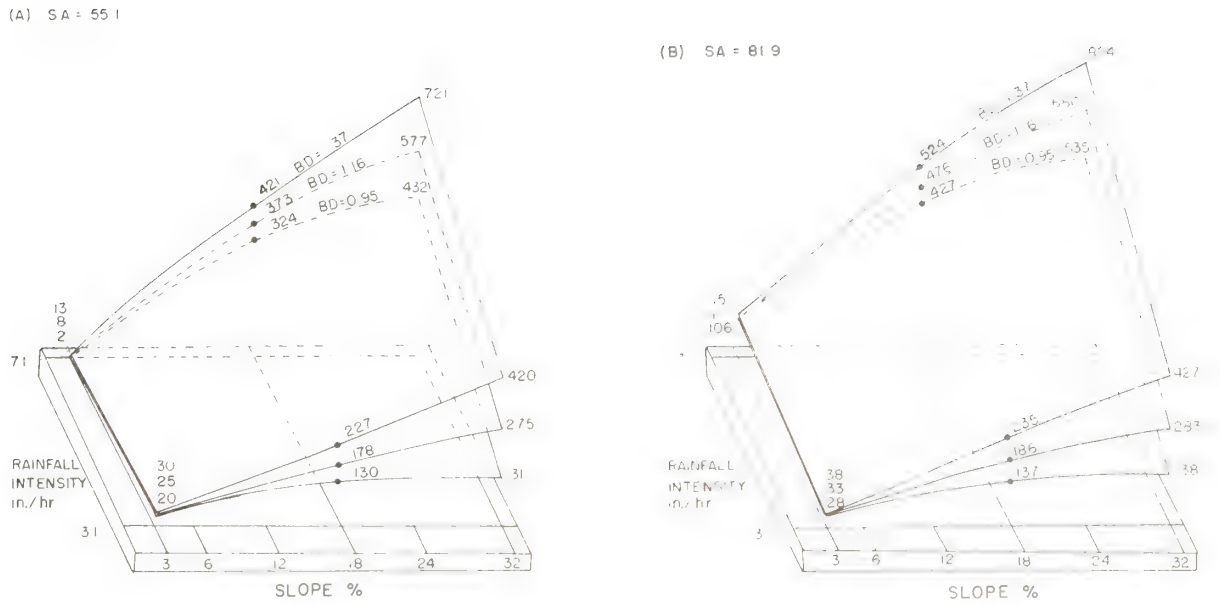

Figure 3.--The relationship between measured soil splash eroded into the bottom pan, rainfall intensity, slope steepness, soil bulk density, and the percent of soil particles and water-stable aggregates between 61 and 2,000 microns, SA, (R^2=0.97). The numbers at the corners of each surface indicate the amount of soil splash in grams. Figure 3A shows the relationship for three values of bulk density and an SA of 55.1 percent; figure 3B is similar except SA is 81.9 percent.

the percent sand-size material (not necessarily sand grains) is also directly related to raindrop erosion. This is illustrated by comparing figure 3A with figure 3B. As the proportion of sand-size material increases from 55.1 to 81.9 percent, the weight of soil eroded by raindrop splash also increases.

The average and maximum absolute deviations from regression were 32.9 g. and 79.9 g., respectively. The mean weight of soil eroded by raindrop splash was 249.0 g.

If the two soil factors, bulk density and proportion of sand-size material, are not included in the interaction model, the resulting R^2 is 0.82. This means that the slope steepness-rainfall intensity interaction accounted for 82 percent of the variance associated with soil-splash erosion; soil bulk density and the proportion of soil material in the sand-size range accounted for approximately 15 percent of the variance.

The proportion of total splash going downhill is quite difficult to measure, but can be estimated on a rational basis (Ekern 1951). On a horizontal soil surface, the soil splash resulting from raindrop impact should be equally divided in all directions. However, assume a unit force of raindrop impact strikes an inclined soil surface in a vertical plane. This impulsive force will result in two component forces, one parallel to the slope in a downhill direction, the second normal to the slope (fig. 4).

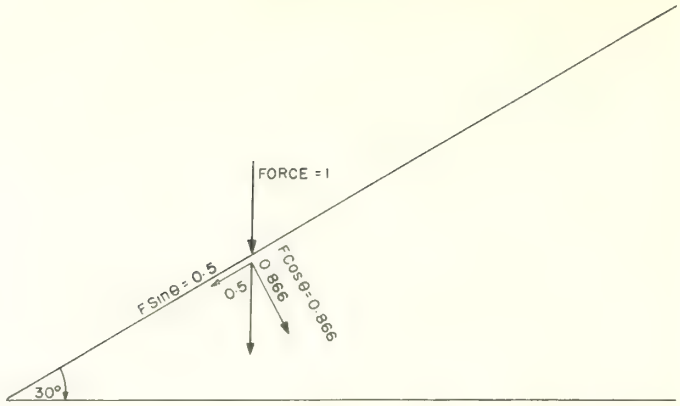

Figure 4.--The resolution of a vertical unit vector force of raindrop impact striking an inclined surface.

Then:

$$Pf = Vf \sin \Theta \qquad EQ(1)$$

where:

Pf = magnitude of the force parallel to the slope;

Vf = magnitude of the force vertical to the slope; and

Θ = slope angle, degrees.

And:

$$Nf = Vf \cos \Theta \qquad EQ(2)$$

where:

Nf = magnitude of the force normal to the slope.

The soil splash resulting from the normal component is assumed to be displaced equally up and down the slope. Therefore, the downslope component of soil splash resulting from a unit force of raindrop impact is expected to be:

$$S_D = \sin \Theta + 1/2 \cos \Theta \qquad EQ(3)$$

where:

S_D = the proportion of total soil splash moving downhill

It is interesting to note that EQ(3) predicts that virtually all soil splash resulting from vertical raindrop impact will go in a downhill direction on all slopes equal to or greater than 37° (75-percent slope). However, this hypothesis was not tested.

The total amount of soil splashed from the soil plot was measured for each of the 18 test runs. EQ(3) was used to calculate the downslope component of the measured total splash. These data were then analyzed by multiple regression methods. Total calculated downslope soil splash was used as the dependent variable. The independent variables were the same as those for the soil splashed into the bottom pan (i.e., slope steepness, rainfall intensity, soil bulk density, and the proportion of total soil particles and water-stable aggregates between 61 and 2,000 microns in diameter). The resulting regression model (figs. 5A and 5B) explains over 92 percent of the variance associated with the calculated total downslope soil-splash erosion, (R^2=0.924).

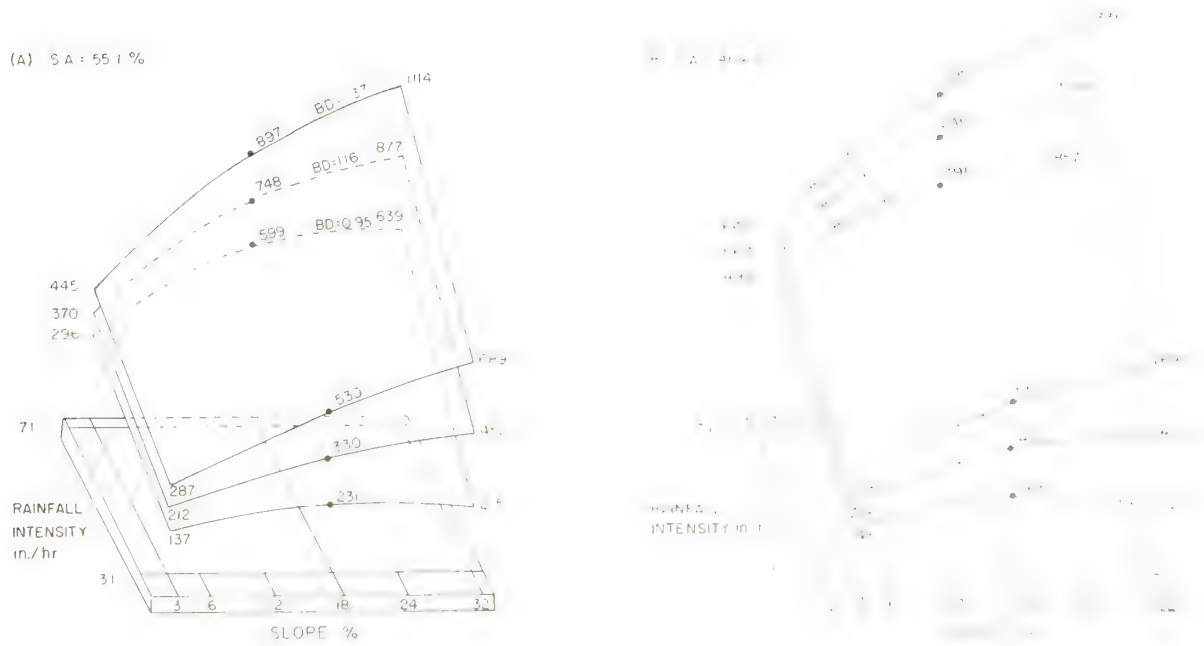

Figure 5.--The relationship between calculated downslope soil splash due to raindrop impact, rainfall intensity, slope steepness, soil bulk density, and the percent of soil particles and water-stable aggregates between 61 and 2,000 microns, SA, (R^2=0.92). The numbers at the corners of each surface indicate the amount of soil splash in grams. Figure 5A shows the relationship for three values of bulk density and an SA of 55.1 percent; figure 5B is similar except SA is 81.9 percent.

Each of the independent variables associated with the models for bottom pan splash and calculated total downslope splash have similar effects. There is the strong interaction between slope steepness and rainfall intensity; bulk density and the proportion of sand-size material both act directly to increase the downslope component of total soil splash.

The average and maximum absolute deviations from the regression model are 66.0 g. and 174.1 g., respectively. The mean weight of downslope splash was 538.8 g. These deviations are about twice as large as those for the bottom pan model (figs. 3A and 3B). This indicates that by calculating the downslope splash component we have added unexplained variation as compared to measured splash in the bottom pan. The addition of unexplained variation is also indicated by the reduction in R^2. Even so, the relatively high R^2 associated with the calculated downslope model is evidence that EQ(3) gave a reasonable estimate of the true downslope component of soil splash due to raindrop impact. This evidence is strengthened by the fact that the same parameters that explain a large proportion of the variance associated with measured splash in the bottom pan also explain a large proportion of the variance associated with calculated downslope soil splash.

If the independent soil variables are dropped from the regression model illustrated in figures 5A and 5B, the resulting R^2 is 0.75. Therefore, while the slope steepness-rainfall intensity interaction accounts for 75 percent of the variance associated with calculated total downslope soil splash, the two soil variables account for an additional 17 percent of the variance. This result is very similar to that of the bottom pan model (figs. 3A and 3B).

Five soil variables--percent of soil particles and aggregates greater than 2 mm., percent of soil particles and aggregates between 61 and 2,000 microns, silt plus clay divided by the mean weight diameter, silt plus clay, and soil bulk density--were used in multiple regression analysis with the calculated downslope splash as the dependent variable. The resulting regression equation gave an R^2 of only 0.31. The failure of soil variables (in the absence of nonsoil variables) to explain an acceptable proportion of the variance associated with soil erosion has been consistent throughout this study. In order to explain as much as one-third of the variance associated with any type of soil erosion on the plots, the slope steepness and rainfall intensity factors must be accounted for. Soil physical factors increase the strength of the regression, but are unable to produce an acceptable regression equation by themselves. On the other hand, the interaction between slope steepness and rainfall intensity explained at least 75 percent of the variance associated with soil erosion.

The distance that soil was splashed off the plot was assessed by the average weighted distance computed for the side splash trays only:

$$\text{Average weighted distance} = \frac{\sum_{i=1}^{4} Xi\ Zi}{\sum_{i=1}^{4} Zi}$$

where:

Xi = distance from the edge of the plot to the center of a splash tray in centimeters

Zi = weight of splashed soil in a given splash tray in grams.

The average weighted distance of splashed soil material did not vary greatly between the three soil types. It was 25.18 cm., 25.31 cm., and 26.42 cm. for the low- and high-elevation granitics and the Wasatch clay, respectively. At a rainfall intensity of 3 inches an hour the average weighted distance was 24.82 cm.; at 7 inches an hour, 26.45 cm. The distance increased more noticeably with slope. It was 22.77 cm., 25.15 cm., and 28.98 cm. for $2\frac{1}{2}$-, 18-, and 32-percent slopes, respectively. These splash distances are for soil material splashed only a single time. Splash distance was not measured directly downslope; so the downslope vector may not be equal to the distances indicated above. However, on steep slopes with multiple splashes, surface soil material could be moved considerable distances downslope irrespective of transport by overland flow.

The size (diameter) of splashed soil material varied inversely with the distance that it was splashed (table 2). As was expected, most of the splashed soil material was in the sand and silt fractions. However, both gravel and clay fractions were found in the splashed soil. Soil material in the clay sizes ordinarily was splashed as aggregates (Wasatch clay) or as clay particles adhering to sand and gravel (Idaho granitics).

Table 2.--*Mean weight diameters in millimeters for each of the pretreatment soils and for splashed soil material by splash distances*

Percent slope	Soil type	Pretreatment soil	Splashed soil			
			Splash distance in centimeters			
			11	34	57	80
21½	High-elevation granitic	1.254	0.992	0.614	0.444	0.404
	Low-elevation granitic	1.164	1.178	.694	.495	.410
	Wasatch clay	.317	.386	.311	.316	[illegible]
18	High-elevation granitic	1.497	.808	.628	[illegible]	.384
	Low-elevation granitic	.898	.857	.578	.506	[illegible]
	Wasatch clay	.585	.461	[illegible]	[illegible]	.288
32	High-elevation granitic	1.466	[illegible]	.688	.062	[illegible]
	Low-elevation granitic	.951	875	[illegible]	[illegible]	[illegible]
	Wasatch clay	.372	.355	.324	[illegible]	[illegible]

ERODIBILITY RANKING BY SOIL TYPE

In order to rank these soils according to their relative erodibility, the regression models illustrated in figures 2 and 5 were solved by using values of the independent variables chosen so as to either maximize or minimize erosion. Each of the soil variables was set at either the maximum or minimum value observed within each soil type (table 3). Soil erosion by overland flow varies directly with rainfall intensity and slope and inversely with the percent of soil particles and aggregates greater than 2 mm.; consequently, the calculated erosion was maximized by using the greatest rainfall intensity, the steepest slope, and the lowest percent of soil particles and aggregates greater than 2 mm. Conversely, soil erosion by overland flow is minimized by using the lowest rainfall intensity, the most shallow slope, and the greatest percent of particles and aggregates greater than 2 mm. Soil erosion due to raindrop splash varies directly with both the soil bulk density and the percent of particles and aggregates between 61 and 2,000 microns. Therefore, raindrop-splash erosion was maximized by using the largest values of rainfall intensity, slope, bulk density, and percent soil material between 61 and 2,000 microns, and minimized by using the smallest values of these variables. The results of these calculations are presented in table 4.

The high-elevation granitic soil appears to be the least erodible of these three soil types. The low-elevation granitic and Wasatch clay types are about equally erodible on a total weight basis; the Wasatch clay is more susceptible to soil loss by overland flow than the low-elevation granitic, but less susceptible to erosion by raindrop splash.

Table 3.--*The observed range and mean values of three soil factors on each of three soil types*

Soil type	Percent[1] of soil particles and aggregates		Bulk density g./cm.[3]
	> 2 mm.	0.061 - 2.0 mm.	
High-elevation granitic	30.4 - 42.6 36.3	49.7 - 58.9 52.6	1.08 - 1.17 1.13
Low-elevation granitic	12.9 - 40.4 23.3	54.5 - 66.6 62.6	1.25 - 1.41 1.31
Wasatch clay	2.5 - 16.5 6.1	72.4 - 81.9 77.1	0.89 - 1.12 1.00

[1]As determined by wet-sieving.

Table 4.--*Calculated values of minimum and maximum erosion due to overland flow and raindrop splash in grams*

Soil type	Soil erosion by overland flow		Soil erosion by raindrop splash	
	Minimum	Maximum	Minimum	Maximum
High-elevation granitic	20	1,306	150	961
Low-elevation granitic	20	1,572	237	1,134
Wasatch clay	31	1,730	112	1,075

Discussion

Soil texture and other soil physical properties indicate that the Wasatch clay soil used in this work is greatly different from the two granitic soils. As a consequence, the soil variables used in these regression analyses covered a wide range of values (table 3). The effects of the soil variables were consistent across soil types. During the analyses for the effect of soil variables, two soil-size fractions were used: (1) greater than 2 mm. and (2) between 61 and 2,000 microns. From the analyses, we were unable to distinguish between the well-aggregated, fine clay soil and the poorly aggregated, coarse-grained granitic soils. Water-stable soil aggregates of a given size class behaved in the same manner as nonaggregated soil particles of the same size.

Stripped of vegetation, all three of these soils exhibit little resistance to erosive forces. High-intensity rainstorms over areas of sparse vegetal cover can be expected to produce tremendous quantities of sediment.

The regression models of soil erosion presented here are not intended for field prediction purposes, but to characterize relationships between the variables observed in the data. Rainfall intensity and slope steepness interact strongly to influence soil erosion by overland flow. This relation, however, is modified by the proportion of soil particles and water-stable aggregates greater than 2 mm. in diameter. This latter factor is really a measure of soil coarseness.

Raindrop-splash erosion is also affected to a large degree by an interaction between rainfall intensity and slope steepness. The effect of soil particles and aggregates between 61 and 2,000 microns is additive and directly related to the amounts of soil splash. Apparently, sand-size material is especially susceptible to splash erosion. During splash erosion, an interaction also takes place between slope steepness and soil bulk density that is not completely understood. In fact, the statistical model for soil splash (figs. 5A and 5B) specifies this relationship imperfectly. On the steep slope at low bulk density the model indicates a small decrease in splash erosion as compared to the medium slope. While splash erosion probably does not increase much between slopes of 18 and 32 percent with soil bulk density less than 1.00, it is not expected to decrease. Ignoring the effect of bulk density, EQ(3) predicts an 11 percent increase in downslope splash for 32-percent slope compared to 18-percent slope. However, an increase in soil bulk density increases the amount of soil splash erosion. On most forest and range soils bulk density exhibits a seasonal increase from the spring to the fall (Laycock and Conrad 1967). Soil splash erosion can also be expected to exhibit an increase from spring to fall.

The strength of the interaction between rainfall intensity and slope steepness is at least a full order of magnitude greater than that of any soil variable, and at least four times as great as any combination of soil variables made in this study. Therefore, it appears that before real expertise can be developed in soil erosion problems due to storm rainfall, information must be assembled on the rainfall patterns and characteristics as well as on topographic effects. Conversely, much of the work in the soil erosion literature describing the effect of soil factors on soil erosion has been concerned with explaining (at best) a small proportion of the variation associated with soil erosion. Comparative erodibilities of soils have been made on the basis of soil factors; these comparisons implicitly assume that rainfall characteristics and topographic effects are equal. Under field conditions this assumption is very questionable. While vegetation was omitted from this study, any realistic evaluation of natural soil erosion must give full recognition to the potentially overwhelming effects of vegetation.

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Provo, Utah (in cooperation with Brigham Young University)

USDA Forest Service
Research Paper INT-101
1971

PAPER CHROMATOGRAPHY FOR DETERMINING PALATABILITY DIFFERENCES IN VARIOUS STRAINS OF BIG SAGEBRUSH

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Federal aid in wildlife restoration funds
was provided through Project W-82-R

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ABSTRACT

Two-dimensional phenolic extraction on 9-inch squares of chromatographic paper was discovered to be a simple laboratory technique for quickly classifying more than 100 foliage collections of big sagebrush from over the Intermountain area into two major palatability classes. These agreed readily with field observations of preferences by deer and livestock on winter ranges. The technique was also in close agreement with the observed preferences by deer of 10 geographic sources transplanted to a common area having a uniform soil within their winter range. It was also useful for quickly recognizing four subgroups in subspecies of *Artemisia tridentata vaseyana* and two subgroups in *Artemisia tridentata tridentata*.

The solvent system for the first dimension was n-butanol, acetone, water (4:1:3) and for the second dimension acetic acid and water (15:85). Chromatograms were viewed under longwave ultraviolet light before and after exposure to ammonia fumes and in daylight following the application of ammonia. The strong association that was found between chromatographic variation and palatability suggests that the procedure may be used to predetermine the grazing potential of any collection of big sagebrush.

The most obvious chromatographic characteristic was the size and intensity of the blue in spot 9. It ranged from large to small and iridescence varied from brilliant to dull. This spot was successfully used to classify all big sagebrush samples into the two basic groups with the other spots being used to make subgroups.

Introduction

Big sagebrush is one of the most widespread and abundant shrubs of the Western United States (Hall and Clements 1923; Beetle 1960; Dayton 1931; and Plummer et al. (1968). It is particularly abundant over much of the Great Basin and in many areas may comprise up to 90 percent of the shrubby vegetation. It is an important browse for big game on their winter ranges. (The nomenclature in this publication has followed Holmgren and Reveal 1966.)

Past observations have revealed that there is considerable variation in the palatability of big sagebrush for big game and livestock. This variation in palatability is often associated with the geographical source of the sagebrush, but in some cases palatable and unpalatable plants may be found growing on a common site. These observations indicate that there may be a real opportunity for development of improved strains through selection and breeding.

Apparently, considerable genetic diversification has occurred in the big sagebrush complex as a result of hybridization and back crossing. Genetic makeup is probably associated with dissimilarities in the chemistry of the plants involved; thus, if chemical differences are detected in plants collected from various geographical sources, this indicates that some degree of genetic divergence exists. Furthermore, the amount of chemical difference may be an index of the extent to which strains have become separated. Such differences in the chemistry of plants have been utilized extensively in recent years to supplement morphological differences in the grouping of closely related plants in some of the major taxa. For example, Hollis (1966, 1967a, 1967b, and 1967c) made comparative analyses of the polyphenols from leaf extracts of *Eucalyptus* using paper chromatography. As a result of these analyses, he resolved many of the problems relating to the taxonomy of this genus. The solution of these problems was not possible on the basis of morphological characters alone.

Similar studies on the genus *Baptisia* were conducted by Alston and Turner (1962, 1963) and Brehm and Alston (1964). In addition, Holbo (1965) completed a comparable study of *Artemisia* section *Tridentatae* in which he readily separated the individual species by chromatography. Using thin-layer chromatography, Brunner[1] showed that strain variation in big sagebrush could be readily detected. Consequently, it appeared likely that similar techniques could be used to separate strains of big sagebrush into palatability classes.

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[1]J. Brunner. Some observations on Artemisia in Nevada. Bureau of Land Management, Las Vegas, Nevada. (Manuscript in preparation.)

Experimental Procedure

From February through September 1969, more than 100 foliage collections of big sagebrush were taken from widely scattered areas in Utah, Nevada, Idaho, Wyoming, and Colorado. We obtained these from a wide variety of sites so that the collections would be fairly representative of the species distribution. In addition to using them in the chemical analyses described below, the degree of grazing by big game was determined to discover if palatability, or preference, was associated with geographical source or ecotype. Observations were made at locations where grazing pressure had not been severe enough to force utilization of unpalatable plants. Generally, the degree of grazing was determined in January, but some observations were made in February and March, and a few were made in April. Palatability was given a low rating where less than 15 percent of the current growth was removed, medium where utilization was 15 to 40 percent, and high where utilization was more than 40 percent. The degree of herbage removal was determined by the technique described by Pechanec and Pickford (1937).

Since we were aware that palatability may be affected by soil or other environmental factors, about 100 plants under 2 years old were collected from each of ten geographical sources of big sagebrush. These plants (totaling about 1,000) were transplanted from their natural sites to comparable randomized rows spaced 3 feet apart on State Fish and Game land located on deer winter range near Price, Utah. Transplanting was done in April and early May of 1968. Plants from three of these sources had been observed to be especially palatable to deer; plants from seven sources had been categorized as unpalatable while growing on their natural sites. The degree of grazing on these transplanted rows was determined in January 1969 and 1970 by the same technique described above.

Foliage collections from plants of the more than 100 sources were placed in brown paper bags and dried in the absence of light. Then, by use of a mortar and pestle, 0.5 grams of the dried leaves were pulverized and placed in brown 30 ml. bottles, and 7.0 ml. of absolute methanol was added to extract phenolic constituents. After 24 hours at room temperature, the extract was decanted and concentrated by evaporation to 2.0 ml. Twenty-five µl of this extract was applied to duplicate 9-inch squares of Whatman No. 3 MM chromatographic grade filter paper in two dimensions. The solvent system for the first dimension was n-butanol, acetone, water (4:1:3) and for the second dimension, acetic acid, water (15:85). Chromatograms were viewed under longwave ultraviolet light before and after exposure to ammonia fumes and in daylight following the application of ammonia in order to note the appearance and color changes of the resulting spots. Each spot was given an arbitrary number for identification purposes and the R_f value of each was computed for both directions of the finished chromatogram.

$$R_f = \frac{\text{Distance of spot from starting point}}{\text{Distance of solvent front from starting point}}$$

The R_f value of a given spot is then expressed as:

$$R_f = R_f \text{ (first dimension)}/R_f\text{(second dimension)}$$

Results

CHROMATOGRAMS

As might be expected when dealing with a large and complex species such as big sagebrush, considerable chromatographic variation was found. Presently, the plant collections have been divided into two major groups, I and II. Group I has 4 subgroups (Ia, Ib, Ic, and Id). Group II has 2 subgroups (IIa and IIb). These groups are based on differences in the chromatographic spots. Chromatograms of each collection always display a basic compliment of ten spots (1, 2, 3, 4, 7, 8, 9, 11, 13, 27) plus varying combinations from an additional eleven spots (5, 6, 10, 12, 14, 16, 22, 25, 26, 33, 36) (table 1 and figs. 1-6). Some of these spots exhibit marked differences in size and intensity of color; therefore, the chromatograms were organized into groups taking into consideration both qualitative and quantitative variations.

Table 1.

Spot no.		Color		
		Ultraviolet	NH_3 + Ultraviolet	
1	.53/.46	Blue	Yellow-green	Gray
2	.90/.78	Violet	Violet	
3	.88/.71	Blue-green	Blue-green	
4	.87/.71	Violet	Violet-brown	Yellow
5	.47/.11	Yellow or Yellowish-brown	Yellow or Yellowish-brown	
6	.28/.13	Yellow or Yellowish-brown	Yellow or Yellowish-brown	
7	.32/.08	Violet	Violet	Yellow-brown
8	.51/.87	Dark blue	Dark blue	
9	.54/.78	Light iridescent	Light iridescent blue-green	
10	.18/.84	Blue	Blue	
11	.34/.75	Blue	Yellow-green	Yellow
12	.26/.71		Blue	
13	.29/.64	Pink	Yellow-pink	
14	.35/.59	Blue or violet	Gray-blue or violet	
16	.32/.90	Dark blue	Dark blue	
22	.32/.84	Blue	Blue-green	
25	.83/.67	Blue-green	Blue-green	
26	.38/.73	Blue	Blue	
27	.51/.57	Blue	Yellow-green	Gray
33	.75/.60	Pink	Pink	
36	.26/.84	Bright blue-green	Bright blue-green	

Figures 1-6.--Representative two-dimensional chromatograms of methanol-soluble extracts from the leaves of the six subgroups (under groups I and II) of big sagebrush. For spot coloration and R_f values, see table 1.

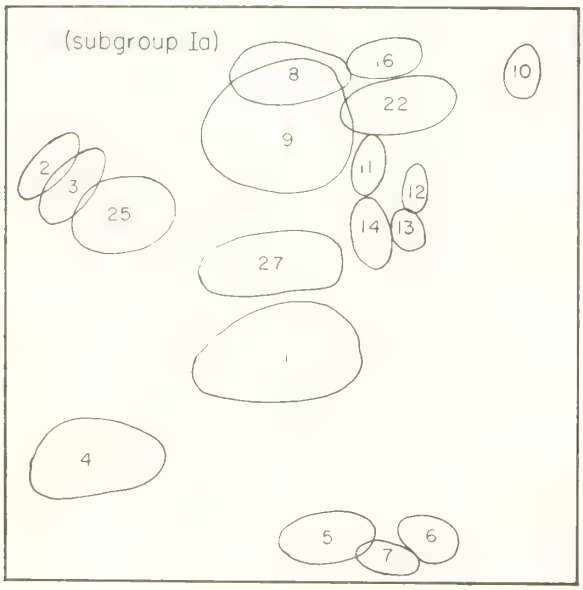

Figure 1

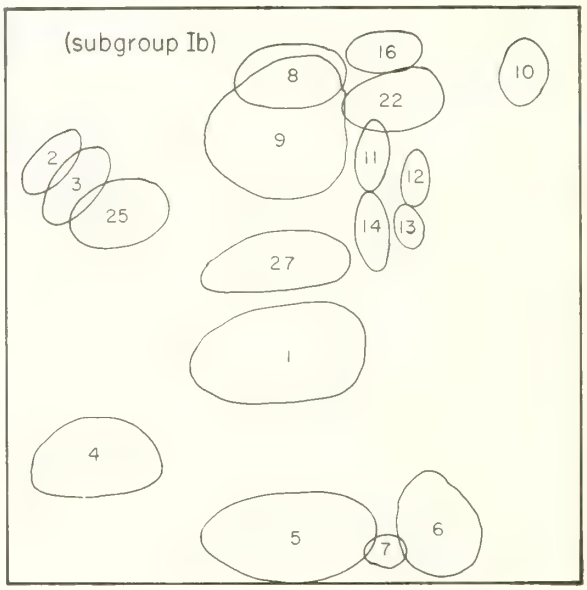

Figure 2

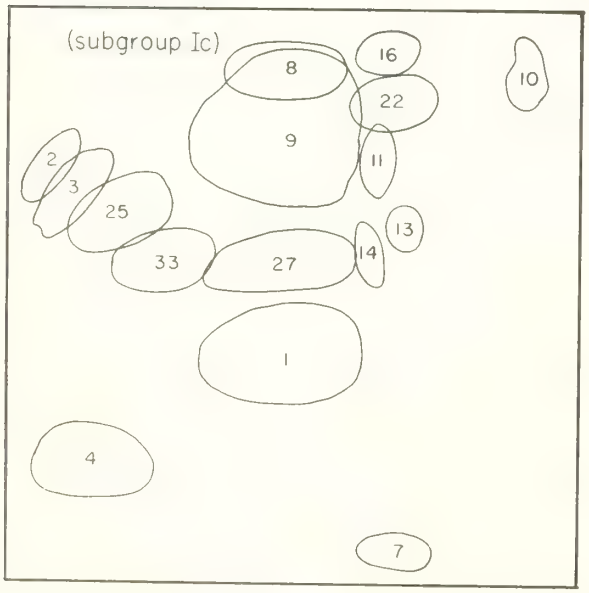

Figure 3

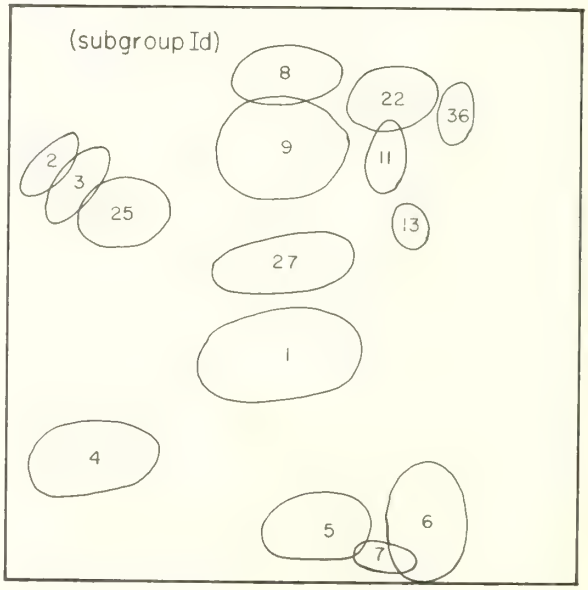

Figure 4

HANKS, DAVID L., BRUNNER, JAMES R., CHRISTENSEN, DONALD R., and PLUMMER, A. PERRY

1971. Paper chromatography for determining palatability differences in various strains of big sagebrush, USDA Forest Serv. Res. Pap. INT-101, 9 p., illus.

Two-dimensional phenolic extraction was found to be a simple laboratory technique for quickly classifying big sagebrush (*Artemisia tridentata*) into palatability classes. The strong association that has been found between chromatographic variations and palatability suggests that the procedure may be used to predetermine the grazing potential of any collection of big sagebrush.

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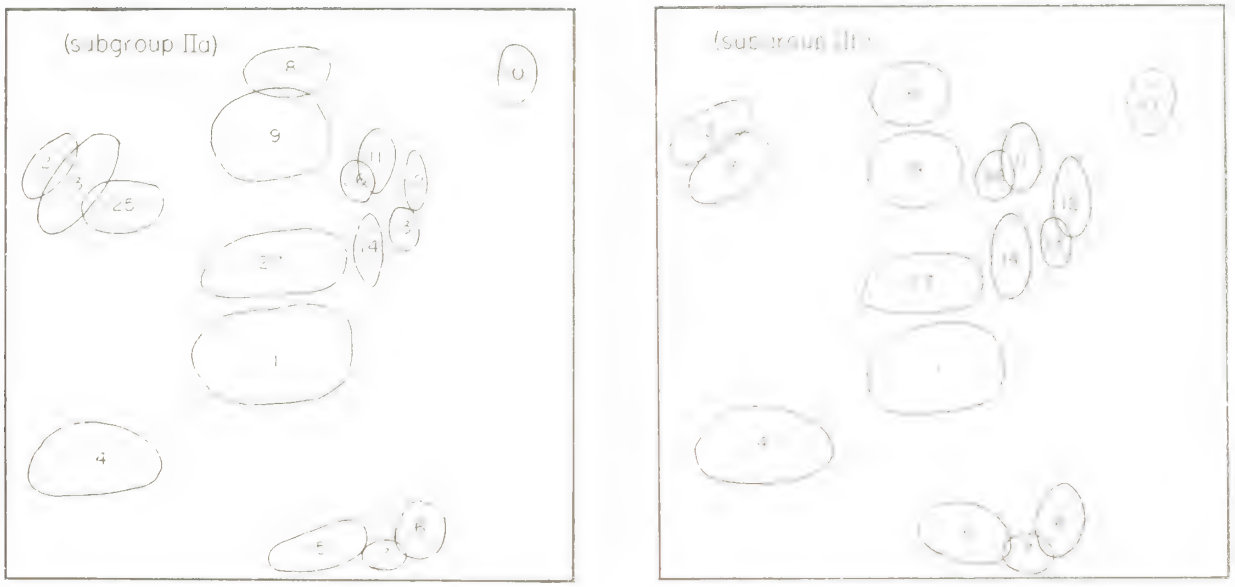

Figure 5

Chromatograms of all collections in Group I contain a large, iridescent blue spot 9 (R_f = .54/.78) which is the most prominent in the entire chromatogram and most characteristic of this major group. In addition, displayed in all specimens of Group I were spots 25 and either 16 or 22 (.83/.67, .32/.90, and .32/.84, respectively). On the other hand, spot 9 of Group II is usually smaller and always less brilliant than in Group I. Furthermore, spot 16 was always absent from the chromatograms of Group II and 22 was found only occasionally. However, spots 5, 6, and 26 (.47/.11, .28/.13, and .38/.73, respectively) were always present in Group II as shown in figures 5 and 6.

Group I.--This major group was subdivided into its four distinct subgroups of Ia, Ib, Ic, and Id (figs. 1-4), on the basis of the following characteristics. In addition to the brilliancy of spot 9, and the presence of spots 16, 22, and 25 mentioned previously, chromatograms of Ia contain spots 5, 6, 10, 12, and 14 (fig. 1). Spots 5 and 6 of this group are relatively small and dull and yellowish-brown in color.

Subgroup Ib differs from Ia only in the size and color of spots 5 and 6, which in Ib are large and bright yellow (fig. 2).

Chromatograms of Ic lack spots 5, 6, and 12 but always contain the prominent pink spot, 33. Spot 9, however, is larger and more brilliant in Ic than in any of the other 3 subgroups of group I (fig. 3).

Subgroup Ic appears to be made up of collections of subspecies *A. tridentata vaseyana* or closely related intermediates within group I. Since this subspecies is such a polymorphic complex, it is possible that Ia and Ib, as well as Ic, may be considered within it.

Group Id lacks spots 10, 12, 14, and 16. Here, spot 9 is intermediate in size but remains highly iridescent. In Id, spots 5 and 6 are large and bright yellow as in Ib. In addition, a bright blue-green spot, 36, is prominent in subgroup Id (fig. 4).

Group II.--This major group was divided into the two subgroups IIa and IIb (figs. 5 and 6), both of which lack spots 16 and 36 but contain spots 5, 6, and 26.

In subgroup IIa, spot 9 is smaller than in any of the previously described subgroups except Id where it is of similar size. However, the brilliancy of this spot in IIa is decidedly less intense than that found in any of the collections placed in group I; nevertheless, spot 9 in IIa remains somewhat iridescent. Spots 12, 14, and 25 occur in this subgroup (fig. 5). In both IIa and IIb, spots 5 and 6 are small and dull yellowish-brown. They are similar in size and color to those found in Ia.

In subgroup IIb, spot 9 is very small, often not exceeding one-half inch in diameter, and it exhibits little or no iridescence. In most chromatograms of subgroup IIb, spots 12 and 25 are missing; and when present they are small and only faintly colored. Spot 14 is always present in IIb, although occasionally the color of this spot is dark violet rather than the usual blue-gray found in all other groups (fig. 6). On the basis of morphological examinations, it seems apparent that collections representing sources in subgroups IIa and IIb would be in the subgenus *A. tridentata tridentata*. Further observations may show IIa to be considerably integrated with Ia.

GRAZING

The groupings already described are related to the degree of grazing by deer and livestock. However, observations indicate that plants in group I are much more palatable than those in group II (fig. 7). This was true on the row plantings on State Fish and Game lands northwest of Price, Utah, in January 1969 and 1970, and also where natural representatives of these two major groups were found on the local winter range.

Figure 7.--Comparison of subgroup Ic from Hobble Creek (left) with subgroup IIb from Indianola, in January 1970, when grazing averaged 60 and 5 percent, respectively. Plants of these sources had attained a similar height of about 24 inches when deer began to graze them in mid-November.

We are confident that differences in palatability exist within groups I and II, but our observations have not yet been intensive or refined enough to detect this and correlate it definitely with chromatographic analyses.

Three of the ten collections planted near Price chromatographed as group I. By mid-January in both 1969 and 1970, all of these were grazed by deer to an average of about 60 percent. None of the big sagebrush plants were grazed less than 40 percent; and on several of the plants, grazing was in excess of 80 percent. In contrast, of the seven collections chromatographed as group II, none were grazed more than 40 percent, and most were grazed less than 5 percent.

All collections from individual *A. tridentata* plants or populations on winter ranges which had been grazed in excess of 50 percent invariably chromatographed as group I except for the single exception represented by a collection from Utah County (Hobble Creek trial site) and involving some big sagebrush transplants. Moreover, all collections from plants or populations observed to be relatively unpalatable on the open range, chromatographed as group II. This was especially noticeable in the area from which collections of subgroups Id and IIa were taken in northwestern Nevada where these two subgroups grow in an intermixed population on a foothill winter range (fig. 8). Subgroup Id on this same range was palatable to the cattle that graze on the area, but IIa was unpalatable and grazed very little. By March 15, 1968, subgroup Id on this range had been grazed slightly in excess of 60 percent, and grazing on IIa was less than 15 percent. The partiality for Id was also exhibited by sheep and deer in that area. The difference between subgroups Id and IIa was also evident on the transplanted areas near Price, Utah. A similar selectivity was also noted where subgroups Ia and Ib intermix with IIb in Ephraim Canyon. Under these intermix conditions, Ia and Ib were grazed in excess of 70 percent by late January of 1969 and 1970, but none of the plants in subgroup IIb were grazed more than 15 percent.

Id IIa

Figure 8.--Marked differences were noted in the size of Artemisia tridentata *subgroups Id (left) and IIa (right) as a result of cattle grazing in the Jackson mountains in northwestern Nevada.*

The most obvious chromatographic characteristic of collections that were selected by deer and livestock was the presence of a large and highly iridescent spot 9. This marker is particularly obvious in subgroups Ia, Ib, and Ic where its brilliance is considerably greater than in the unpalatable subgroups; however, this distinction is not so clear in regard to Id and IIa. Since subgroups Id and IIa are found in close physical association, the use of additional characters is frequently necessary. Other indicators of palatability for deer and livestock are the presence of spots 16 and 22 in subgroups Ia, Ib, and Ic; the presence of 22 in Id; and the absence of 26 in all groups.

Discussion

At this point in our study of the big sagebrush complex, we believe it is significant that chromatograms of the various collections allow rather well-defined groupings. The existence of these groups not only supports our initial hypothesis regarding the occurrence of genetic divergence within subspecies of big sagebrush, but provides evidence that this genetic change is following quite discrete lines. However, we must point out that some of the collections do not fall into any of the designated groupings but appear to occupy positions intermediate between them. Chromatograms of these intermediates most commonly contain both spot 22, found primarily in group I, and 26 occurring in group II; but such chromatograms lack spot 16 found in group I, and spot 9 is usually intermediate in brilliancy. This combination suggests hybridization between groups I and II and the retention by the progeny of some characteristics from each parent. Nevertheless, the majority of collections can be readily separated into the previously described groupings by the methods given.

In regard to the ecological distribution of the major groups and subgroups, the following observations have been made. Collections of group I were obtained primarily in mountain habitats. Those of subgroup Ic were obtained in the lower mountains and higher foothill areas. Individuals from subgroups Ia and Ib of the lower foothills area have come from areas extending from the lower limits of Ic to the base of the foothills where they overlap with subgroup IIb, the prevalent big sagebrush (*A. tridentata tridentata*) of the more extensive lowlands.

The two subgroups Ia and Ib occupy the lower foothill areas, and it appears that Ia predominates in the upper portion while most collections of Ib have come from the lower part. However, specimens of each have been collected throughout this entire range.

Subgroups Id and IIa have only been collected from areas on the Jackson and Pine Forest mountains in northwest Nevada where they occupy similar habitats.

Chromatograms of the tall bushes commonly observed growing along such places as fencerows and arroyos differ slightly from those of IIb, among which they are frequently found. However, too few collections have been analyzed to warrant the formation of a separate subgroup at this time, although it appears likely that this may be advisable following a more thorough study. In the present paper, this tall fencerow type is included in IIb. Thus, on the basis of source material, it seems significant that the distribution pattern fits fairly close to the chromatographic divisions, especially between highland and lowland sources.

There is little likelihood that phenols observed in the big sagebrush of this study are responsible for the relative palatability of these plants. However, the strong association that has been found between chromatographic variation and palatability suggests that this laboratory procedure may be utilized to quickly evaluate the grazing potential of any collection of big sagebrush. Consequently, chromatography can be a useful tool in selecting strains of big sagebrush for specific purposes.

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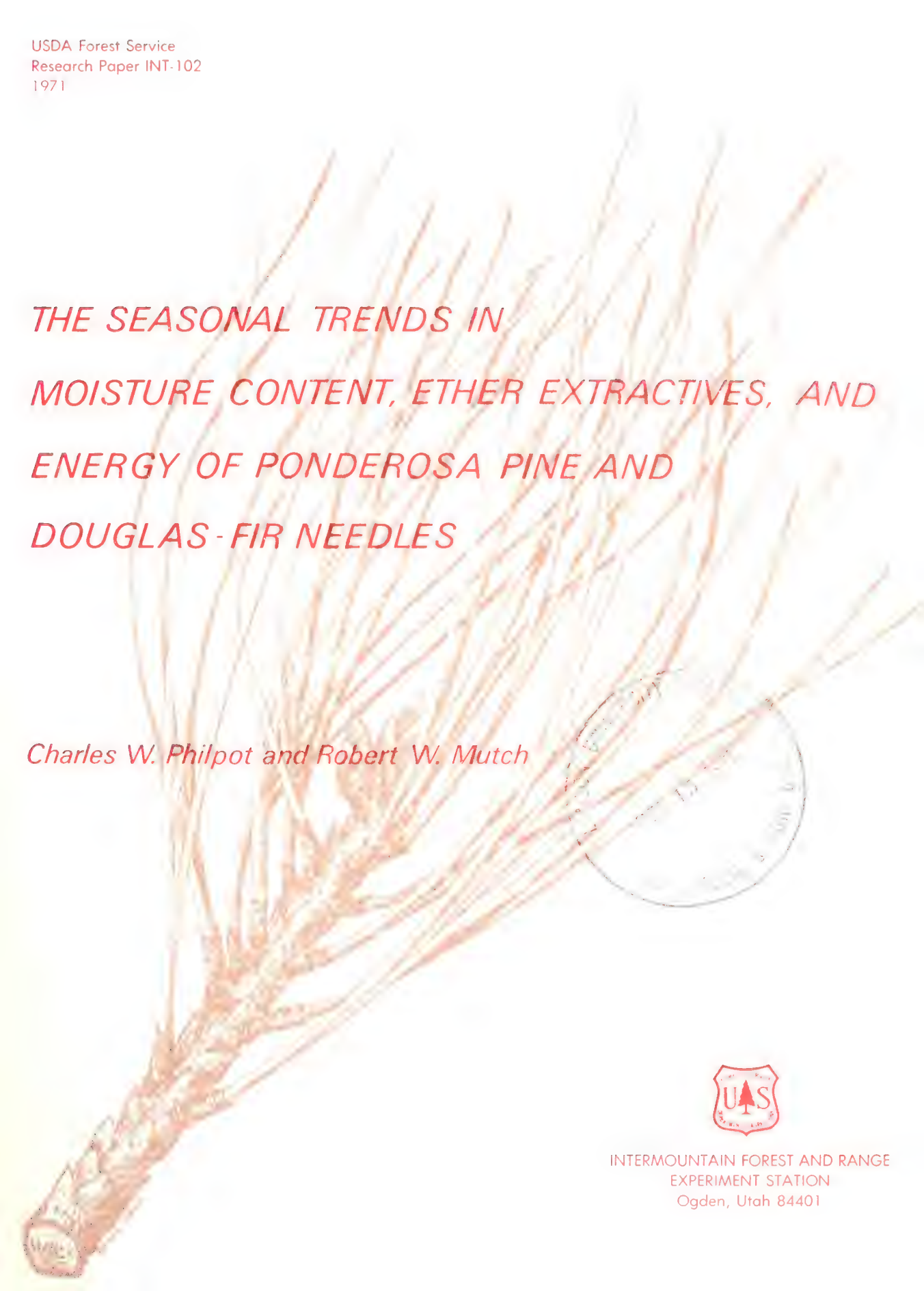
USDA Forest Service
Research Paper INT-102
1971

THE SEASONAL TRENDS IN MOISTURE CONTENT, ETHER EXTRACTIVES, AND ENERGY OF PONDEROSA PINE AND DOUGLAS-FIR NEEDLES

Charles W. Philpot and Robert W. Mutch



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The authors wish to thank Walter H. Wallace, Research Technician, Gerhardt C. Lenz, Research Aid, and Roberta Dvorak, Research Aid, all of the Northern Forest Fire Laboratory, for their excellent technical help on this study.

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ABSTRACT

The moisture, ether extractive, and energy content of ponderosa pine (*Pinus ponderosa* Laws.) and Douglas-fir (*Pseudotsuga menziesii* L.) foliage were measured during two fire seasons. The moisture content of 1- and 2-year-old needles was found to rise throughout the summer. The ether extractive content was highest in the fir foliage at the end of summer when fire severity is generally thought to be highest. Pine foliage extractive content was high throughout the sample period. The energy content of the extracted leaves and the extractives varied through the summer. There may be a relationship between the extractives and crown fire potential in these species.

INTRODUCTION

Why does fire behavior show a seasonal change? Generally speaking, this occurs because of changes in the fire environment. Moisture content traditionally has been cited as the important change in fuel that conditions flammability and fire behavior (Hawley 1926; Davis 1959). The moisture contained in fuels is important because it acts as an energy sink, diluting the volatiles, and excluding oxygen from the combustion zone. There are many studies on moisture content of living plants,[1] but only a few apply to this paper that discusses moisture, ether extractives, and energy of conifer crowns.

In the late 1930's Connaughton and Maki[2] found that moisture content of ponderosa pine foliage varied inversely with soil moisture and climatic drying during the fire season in northern Idaho. The fact that moisture content increases in ponderosa pine foliage during June, July, and most of August is interesting since crown fires are more prevalent as the fire season progresses in this region.

Philpot found the same general situation in ponderosa pine in the central Sierra Nevada of California with moisture increasing through most of the fire season and then leveling off.[3] A similar trend was also found for pinyon pine and juniper in Arizona and Utah (Jameson 1966), and for five coniferous species in eastern Canada (Van Wagner 1967). After finding high moisture contents in conifers in the Lake States during periods of high crown fire potential, Johnson (1966) concluded, "In our search for a satisfactory explanation for crown fires, we must apparently look beyond needle moisture content."

Can our concept of fire environment go beyond the commonly accepted fire climate-fuel moisture basis of fire occurrence? Dry seasons and moisture content regimes certainly determine the actual fire seasons, but recent studies suggest that inherent plant chemistry and chemical changes contribute materially toward the availability of energy to the combustion process (Philpot 1968, 1969a). Plant communities which have survived fires for tens of thousands of years may not only have selected survival mechanisms, but also inherent flammable properties that provide a competitive advantage and contribute to perpetuation of fire-dependent communities (Mutch 1970). This broader concept of fire environment encompasses not only moisture relations, but inherent energy and physical properties as well.

Since living foliage contributes significantly to the energy field of many large fires, the objective of this study was to determine simultaneous trends of moisture contents, ether extractives, and heat contents for Douglas-fir *(Pseudotsuga menziesii* L.) and ponderosa pine *(Pinus ponderosa* Laws.) foliage during the 1968 and 1969 fire seasons. These three variables should be studied together to arrive at meaningful conclusions about their relative importance to seasonal fire behavior.

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[1]C. W. Philpot. Vegetation moisture trends in the central Sierra Nevada. (Unpublished master's thesis on file at School of Forestry, Univ. of Calif., Berkeley) 53 p., 1963.

[2]C. A. Connaughton and T. E. Maki. The volatility content (particularly moisture) of evergreen foliage during periods of drought stress. (Unpublished office report, U.S. Forest Serv. on file at Intermountain Forest and Range Exp. Sta., Northern Forest Fire Lab., Missoula, Mont.) 1935.

[3]Philpot, op. cit.

An understanding of the energy levels is essential to the quantitative study of combustion in wildland fuels and the definition of such fundamental variables as fuel energy, fire intensity, combustion rate, and heat yield. Byram (Davis 1959) emphasized this point by stating that, "The energy which maintains the chain reaction of combustion is the heat of combustion--a quantity which can be measured for any particular fuel."

Heat content values have been reported for a wide variety of wood fuels, but energy studies of lesser vegetation have probably received most attention from ecologists interested in the application of caloric values to the energy relationships of ecosystems (Long 1934; Golley 1961; Bliss 1962). Golley (1961) concluded that prior to making intensive measurements of energy flow the heat contents must be determined under the specific conditions of a particular study because of variability of plant material. His examination of more than 600 records of plants indicated that significant differences in heat content exist between plant parts, between vegetation collected in different months, and between vegetation growing in different ecological communities. Bliss (1962) found that heat content values for the anatomical parts of evergreen shrubs exceeded those for deciduous shrubs in nearly all cases; however, a significant difference was not established. Amiot (1959) found that the heat of combustion of litter samples differed considerably by forest type; the more coniferous trees the stand contained, the higher was the heat of combustion of its litter. Variations in heat content by needle age, elevation, and season of year were determined for five coniferous species at the Priest River Experimental Forest in Idaho during 1962 and 1963 prior to this current study[4] (table 1). Hough (1969) recently determined the energy values of some forest fuels from the southern United States.

Species			1963	
	ft.	2,620 ft.	2,500 ft.	ft
New	8,268±3		8,419±51	8,486±12
	8,698±12	8,735±4		8,885±10
				8,862±28
				8,806±16
Dead ground	8,747±21	8,866±23	8,677±11	8,627±15
	2,240 ft.	2,500 ft.	2,240 ft.	2,500 ft.
		8,676±11	8,325±10	
1 year		8,675±23	8,743±19	8,553±33
2 year		8,752±15	8,803±20	8,568±41
				8,593±17
and/or tree	8,752±15		8,540±14.2	8,446±19
	2,300 ft.		2,300 ft.	5,040 ft.
			8,486±4	8,544±10
1 year		8,972±28	8,712±8	
	8,962±11		8,799±14	8,963±34
		9,113±18	8,846±18	9,057±34
4 year		9,186±27		9,083±10
	2,240 ft.	3,900 ft.	2,240 ft.	
	8,594±11		8,612±11	8,510±28
	2,300 ft.	3,900 ft.	2,240 ft.	3,900 ft.
			7,961±7	7,904±9

[4]R. W. Mutch. Caloric content in coniferous needles. (Unpublished office report USDA Forest Serv., on file at Intermountain Forest and Range Exp. Sta., Northern Forest Fire Lab., Missoula, Mont.). 1963.

Table 2.--*Lower limits of flammability of gases in air*[1]

Gases	Percent gas to air
Methane	5.00
Propane	2.12
Butane	1.86
Ethanol	3.28
Diethyl ether	1.85
Hydrogen	4.00
Ethylene	2.75
Acetylene	2.50
Octane	.95
Turpentine[2]	.80

[1]Handbook physics and chemistry, 38th Ed., p. 1788, 1956-57. Chemical Rubber Publishing Co.

[2]α + β pinene

The ether extractives (crude fat content) are composed of many compounds, including oils, waxes, fats, and terpenes. Crude fat content is directly related to the total energy content of plants (Bliss 1962; Philpot 1969b). These extractives could be important for several reasons: first, they have a very high energy content, up to 23,000 B.t.u./lb.;second, a portion of them is more available to combustion than the other major components of the fuel because of their high vapor pressure and, in some cases, because of their location on fuel surfaces (Philpot 1969b). Also, terpenes have one of the lowest fuel/air ratios of any organic fuel (table 2). They vary seasonally in many fuels, reaching a maximum at the height of the fire season (Philpot 1969b; Richards 1940). For example, consider the trend in ether extractives in aspen leaves during the 1968 fire season in western Montana (fig. 1). The energy increase in fuels during the fire season is due mainly to extractive accumulation or changes in extractive composition.

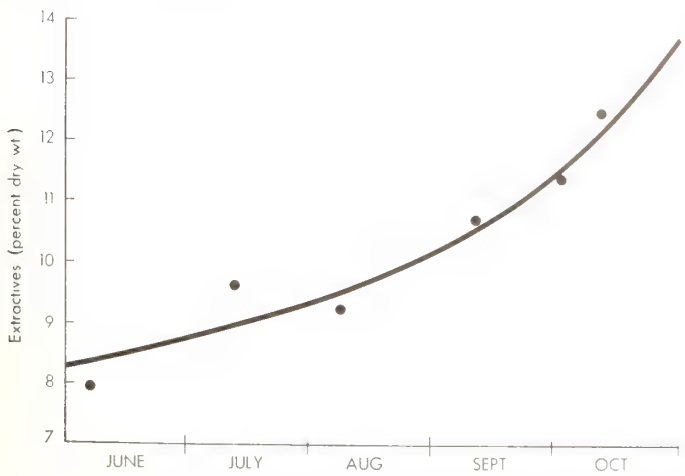

Figure 1.--The trend of ether extractive content in aspen during the fire season in western Montana.

METHODS

Two sites in western Montana with mixed ponderosa pine and Douglas-fir, approximately 1 acre each, were used for this study. In 1968 the moisture content, ether extractive, and energy data were collected from a stand at 3,500 feet, southwest exposure, and 58-percent slope. The ponderosa pine averaged 24 feet high and 4.9 inches d.b.h. The Douglas-fir averaged 31 feet high and 5.2 inches d.b.h. Physiological changes that might result from the large amount of foliage sampling required in this study necessitated a change of site in 1969. The 1969 site was at 3,840 feet, southwest exposure, and less than 10-percent slope. On this site, the pine averaged 39 feet high and 10.9 inches d.b.h., and Douglas-fir averaged 38 feet high and 8.5 inches d.b.h. All trees were dominant or codominant.

Twelve trees of each species were randomly tagged on each site. Three trees of each species were randomly chosen for sampling on a given date. All sampling occurred between 1300 and 1600 hours to minimize the effect of diurnal variation.[5] Two branches from each tree were cut from the middle one-third of the south side of the crown. A portion of the needles of each age class (new, 1 year, and 2 years) was immediately sealed in a tared 500 ml. flask. These flasks were placed in an insulated container in the field and the same flasks were used for moisture determination by solvent distillation (fig. 2). The foliage for extractive and energy determinations was placed in an insulated chest and frozen with dry ice. The frozen samples were separated by age class and placed on a freeze dryer for 14 hours. They were then ground in a Wiley mill and sifted to 40-60 mesh. Ether extractives (AOAC 1965) and heat content (ASTM 1967) were determined by standard methods. Energy content of untreated and ether extracted 1-year-old foliage samples was determined. All extractive and energy data were reduced to a dry weight basis by Karl Fischer titration (ASTM 1962).

Precipitation, temperature, and humidity were measured at a nearby fire-weather station and the buildup index was computed (USDA Forest Service 1964). The moisture and extractive content data were statistically analyzed using Tukey's test (Snedecor 1956).

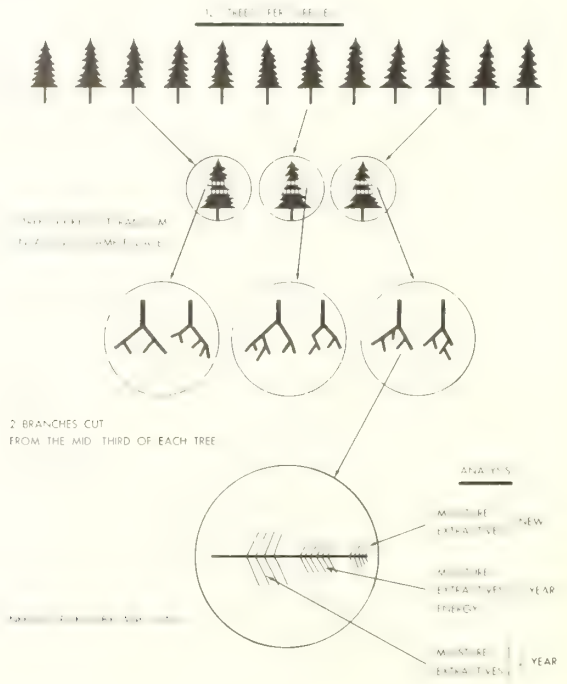

Figure 2.--The foliage sampling scheme used for ponderosa pine and Douglas-fir

[5]Philpot, op. cit.

RESULTS

Weather Factors

The two "fire seasons" differed quite drastically in terms of temperature, humidity, and precipitation trends. Perhaps the most striking difference was in quantity and distribution of precipitation (fig. 3). The main difference between humidity patterns for 1968 and 1969 occurred after August 1. During 1968, the average humidities at 1630 hours were around 40 percent or higher throughout August and September. However, during 1969 humidities averaged 20 percent and did not rise above 30 percent until mid-September. Temperatures during the same period averaged about 20° higher in 1969.

The National Fire-Danger Rating Buildup Index, which accumulates daily drying conditions by integrating temperature, humidity, and rainfall, was plotted for 1968 and 1969 (fig. 4). On August 12 of both years the index had reached 200 or above. The index dropped to below 25 on August 13, 1968, and remained below 50 for the rest of the summer. In 1969 the index kept climbing until it reached 380 on September 18, at which time it dropped due to the first fall rains. These weather data show that the months of August and most of September were wet and cool in 1968 and dry and hot in 1969.

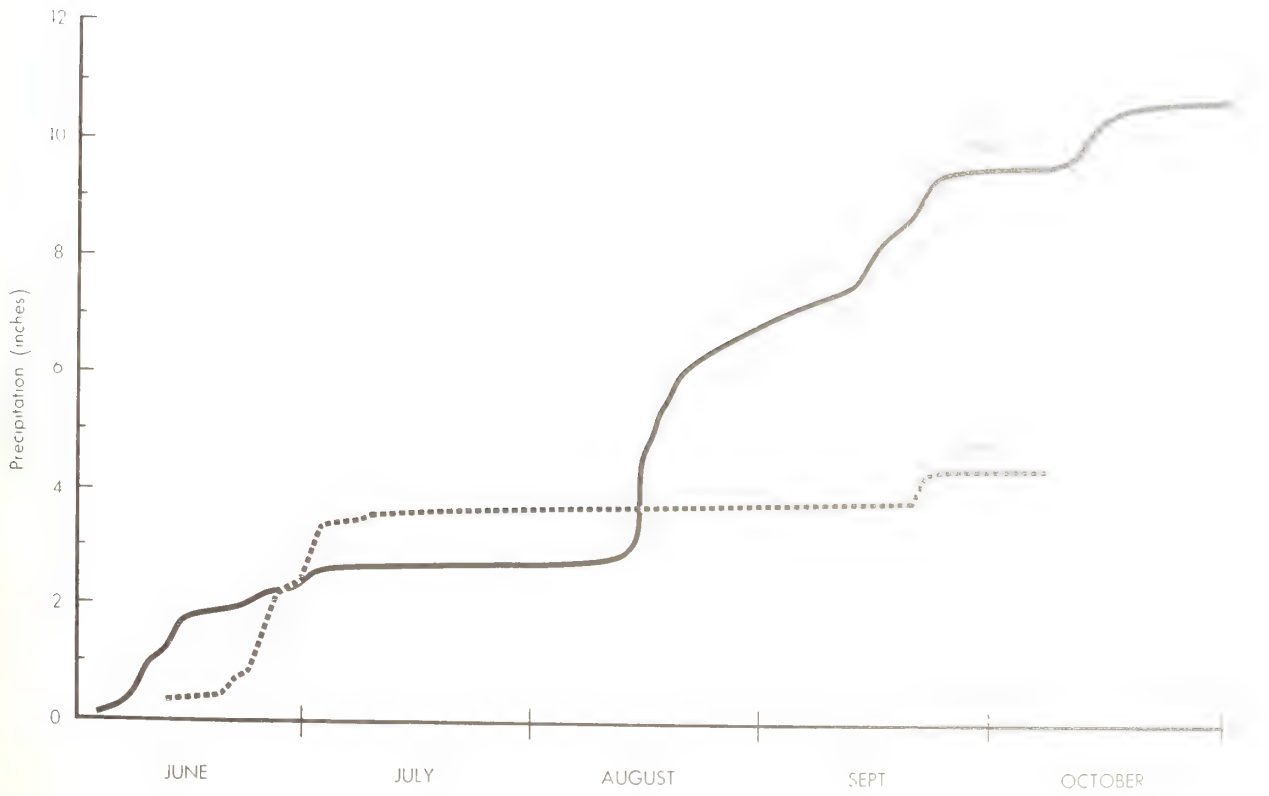

Figure 3.--The accumulated precipitation during the 1968 and 1969 fire seasons.

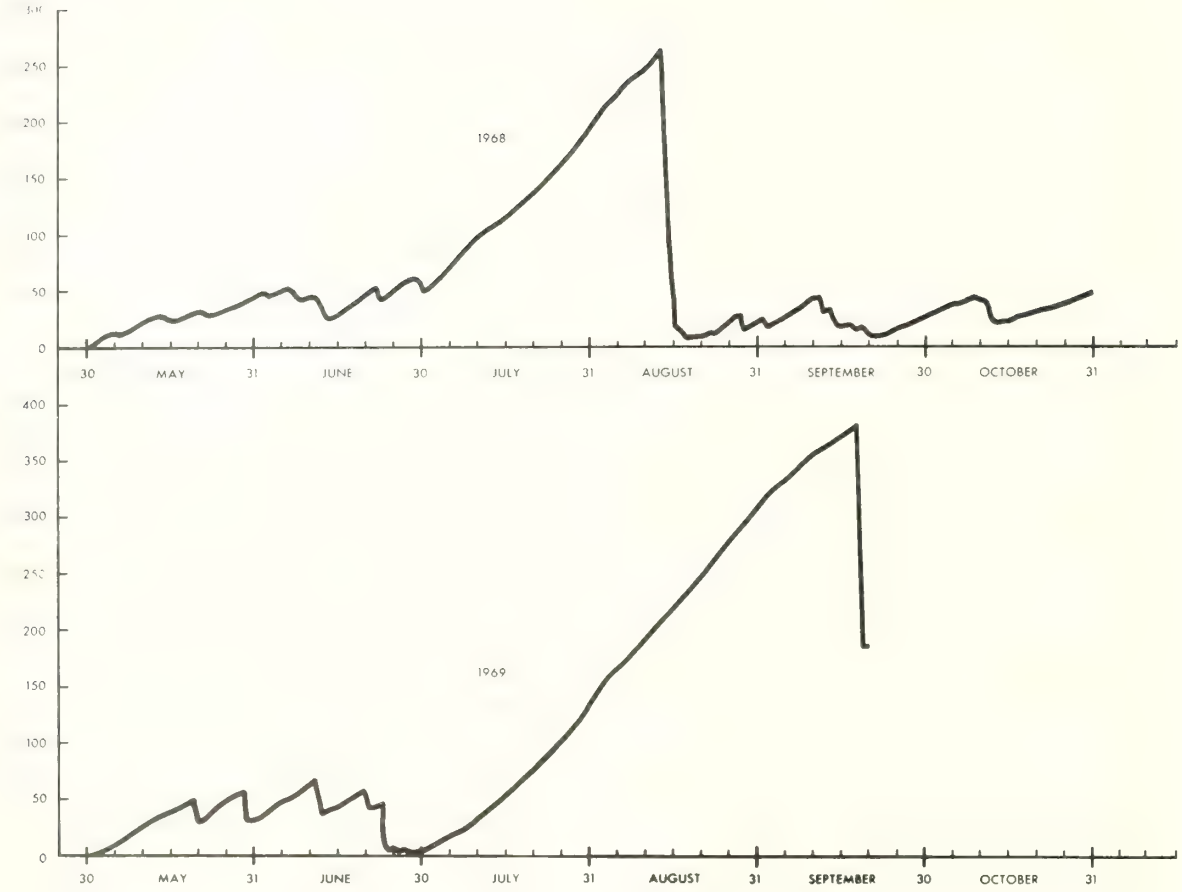

Figure 4.--The buildup index for 1968 and 1969.

Needle Moisture

The percent moisture content of new pine and fir needles fell from above 200 percent (dry weight) in June to about 130 percent by mid-August for 1968 and 1969, although there is an apparent difference in trends between years (figs. 5, 6, 7, and 8). However, the mature pine and fir needles began the fire season well below 100 percent. In fact, Douglas-fir needles (1 and 2 year) were below 80 percent in June 1968. All mature needles appeared to gain moisture during the fire season, reaching levels of 110 to 120 percent. Very little if any gain occurred past mid-August.

The moisture content trends for 2-year-old pine and fir needles collected during the 1968 fire season were statistically significant. The same is true for: 1-year-old pine, 1968; 2-year-old pine, 1969; and 1-year-old fir, 1969 (Appendixes A, B, C, and D). Also, the trends for all new needles were statistically significant.

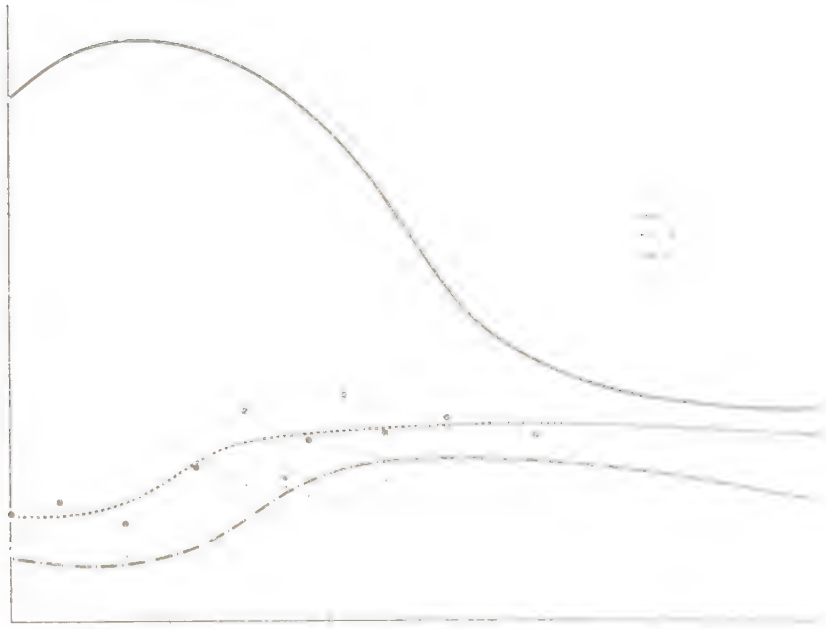

Figure 5.--The moisture content of ponderosa pine needles during the 1968 fire season.

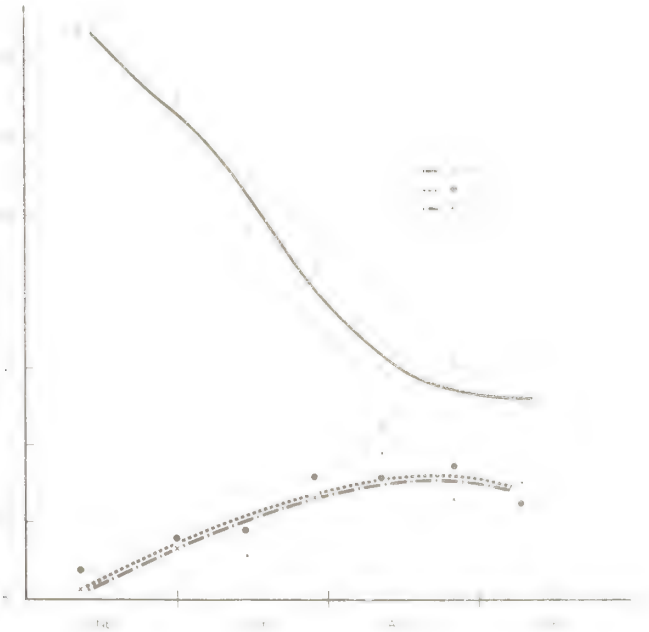

Figure 6.--The moisture content of ponderosa pine needles during the 1969 fire season.

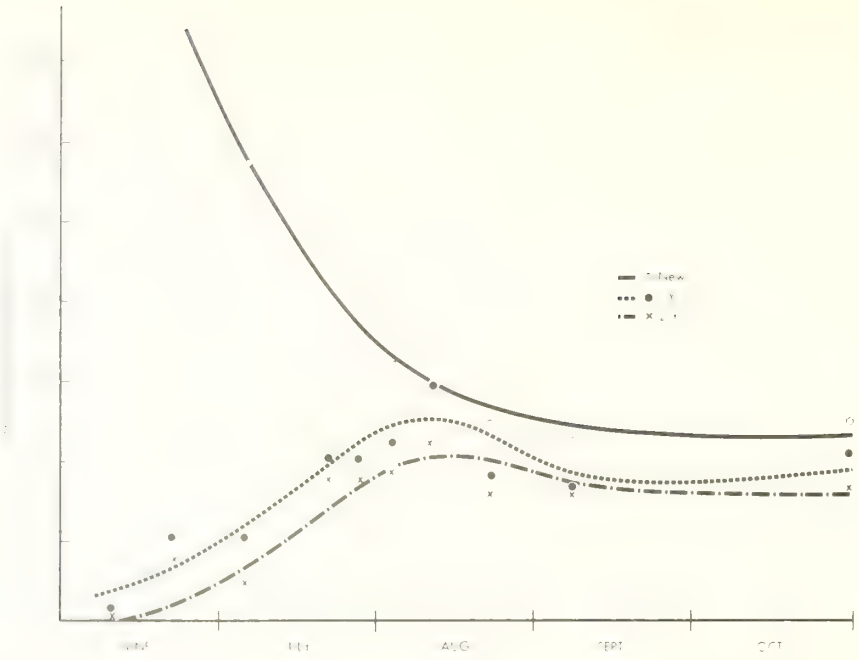

Figure 7.--The moisture content of Douglas-fir needles during the 1968 fire season.

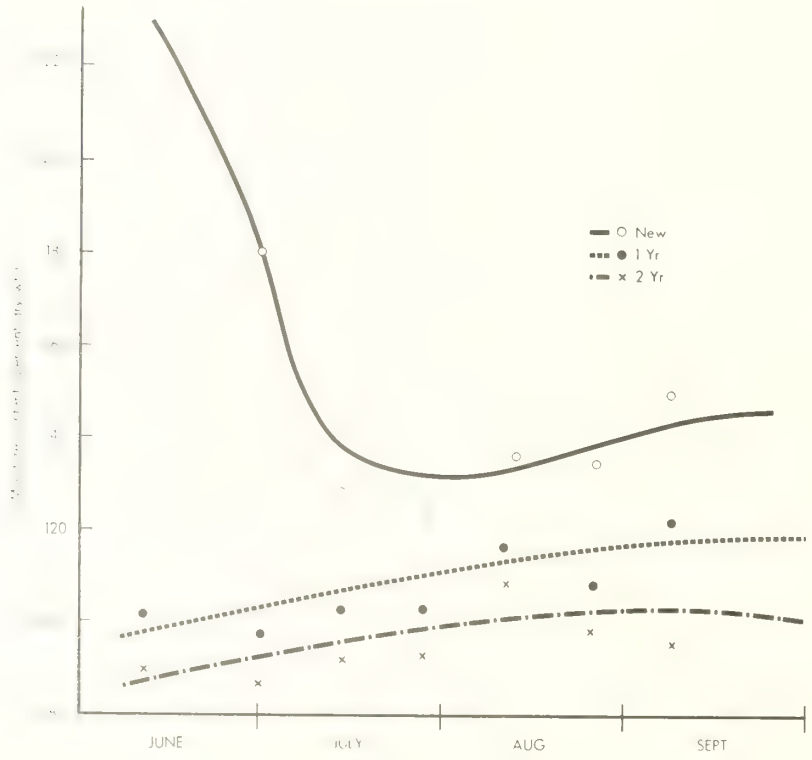

Figure 8.--The moisture content of Douglas-fir needles during the 1969 fire season.

Extractives

During both summers, Douglas-fir needles showed much more change in extractive content than did ponderosa pine. In 1968 fir needles gained in extractives until mid-August, at which time they decreased (fig. 9). This trend was statistically significant at the .05 level (fig. 10) (Appendix E). Pine showed a similar trend of lower magnitude in 1968, but it was not significant (Appendix F). Pine showed little or no change during 1969, but fir had a significant increase from 4-1/2 to 8 percent during the 1969 fire season (figs. 11 and 12) (Appendixes G and H).

An interesting aspect of these trends is the difference between 1968 and 1969. The mid-summer decrease in 1968 coincided with the onset of precipitation, while during the dry year the gain in extractives continued through to September. Pine seemed to maintain a high extractive content (8-9 percent) during both fire seasons, but a dip did occur in 1968 in early August. Tukey's test (1956) showed this dip to be statistically insignificant.

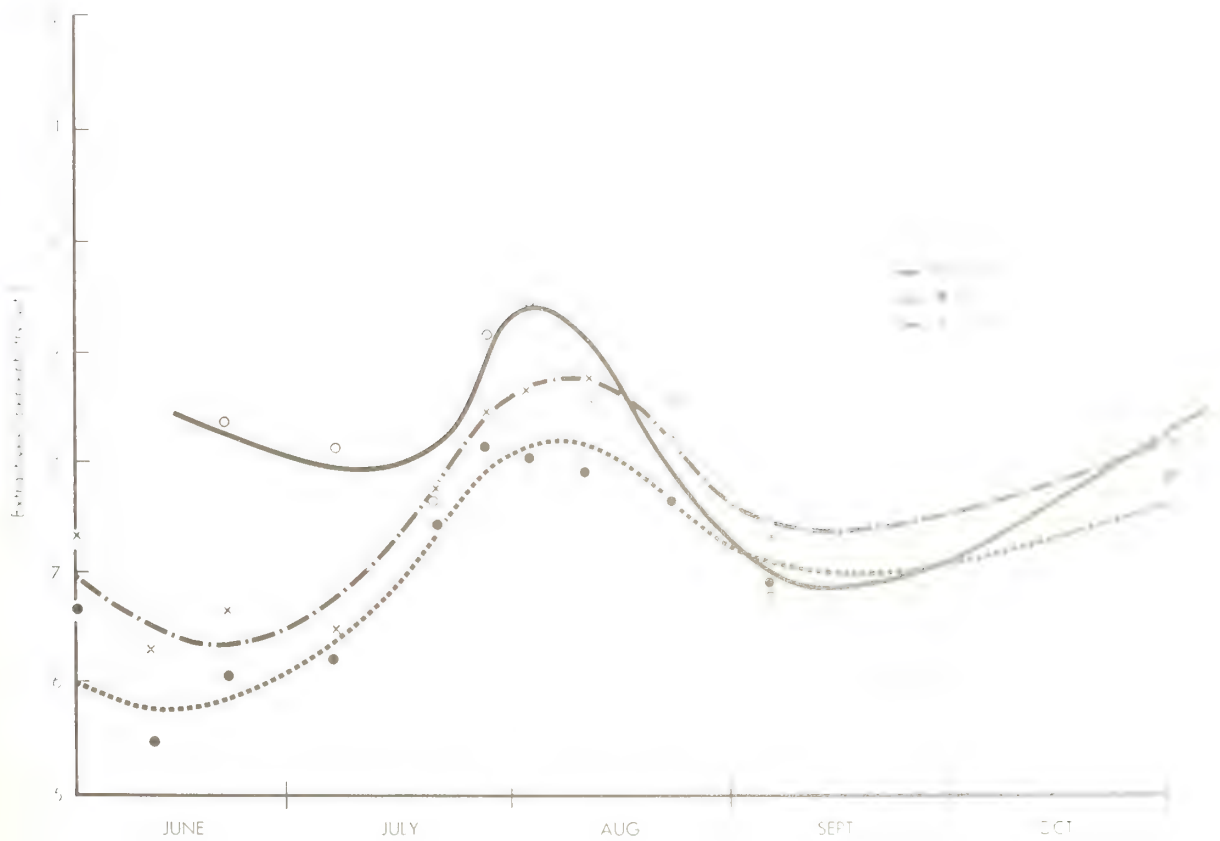

Figure 9.--The ether extractive content of Douglas-fir needles during the 1968 fire season.

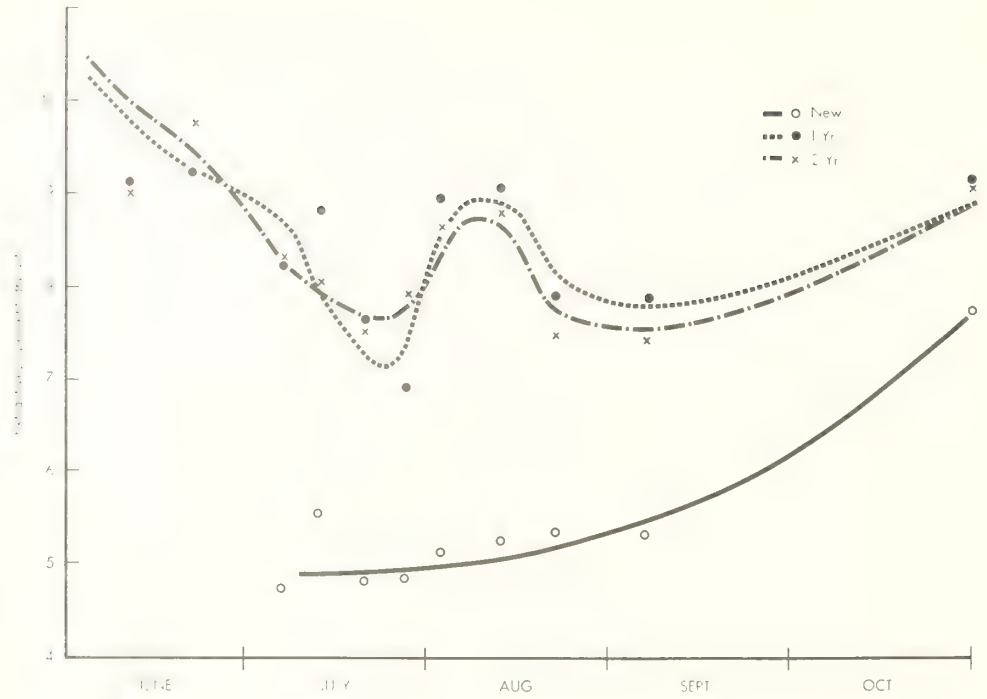

Figure 10.--The ether extractive content of ponderosa pine needles during the 1968 fire season.

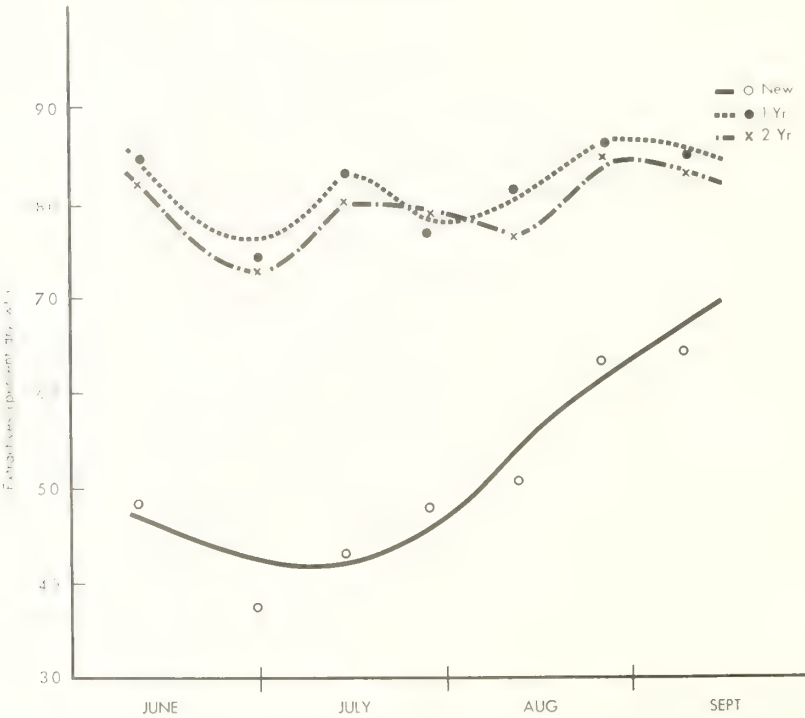

Figure 11.--The ether extractive content of ponderosa pine needles during the 1969 fire season.

PHILPOT, CHARLES W., and MUTCH, ROBERT W.

1971. The seasonal trends in moisture content, ether extractives, and energy of ponderosa pine and Douglas-fir needles, USDA Forest Serv. Res. Pap. INT-102, 21 p., illus.

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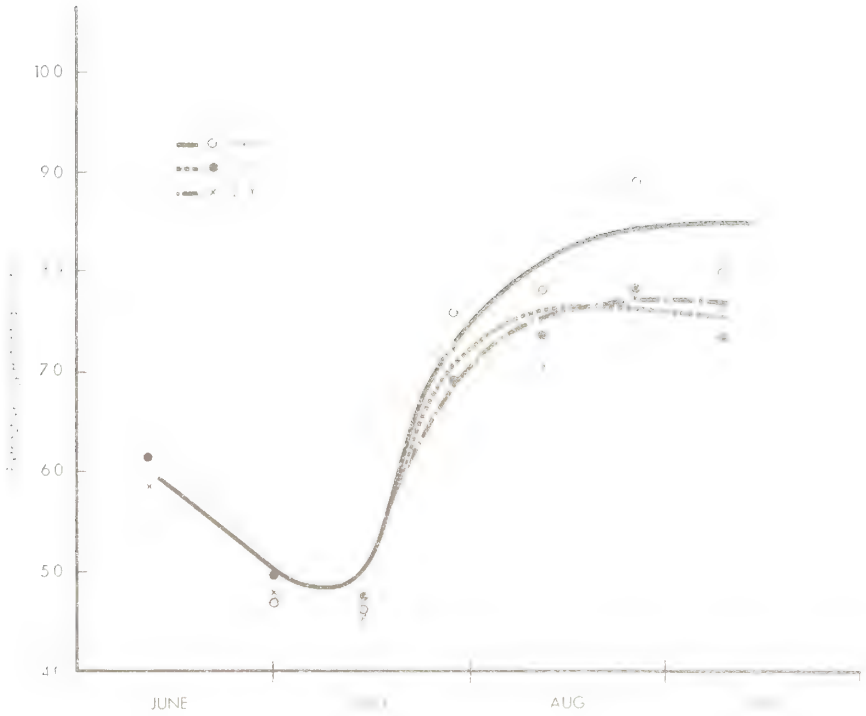

Figure 12.--The ether extractive content of Douglas-fir needles during the 1969 fire season.

Energy Content

The energy content of fir needles showed the most increase during the fire season, amounting to about 700 B.t.u./lb. in 1968 and 500 B.t.u./lb. in 1969 (figs. 13 and 14). Pine gained 400 and 200 B.t.u./lb. respectively (figs. 15 and 16). Pine showed a decrease during both years up to August and then an increase; fir generally gained during the summer. Most of this gain in fir was due to an increase in extractive content in 1969, while no similar trend occurred in 1968. (H_{diff} = difference between total energy content, H_{tot}, and energy content of the extracted needles, H_{ext}.) The extractives from Douglas-fir and ponderosa pine average about 16,000 B.t.u./lb. with a range of 14,000 to 20,000 B.t.u./lb. The increase in energy content of the fir in 1968 was due mainly to the energy change in the extracted needles. These data were not subjected to statistical analysis because the extensive time involved in calorimeter runs resulted in a limited amount of data. Generally speaking, these data show that fir gains in energy during the fire season, while pine decreases from May to August and then gains again. The change in fir is due to the change in extractive content and energy content of the extracted needles. The change in pine is apparently caused by a change in energy content of the extractives themselves, which implies a compositional change.

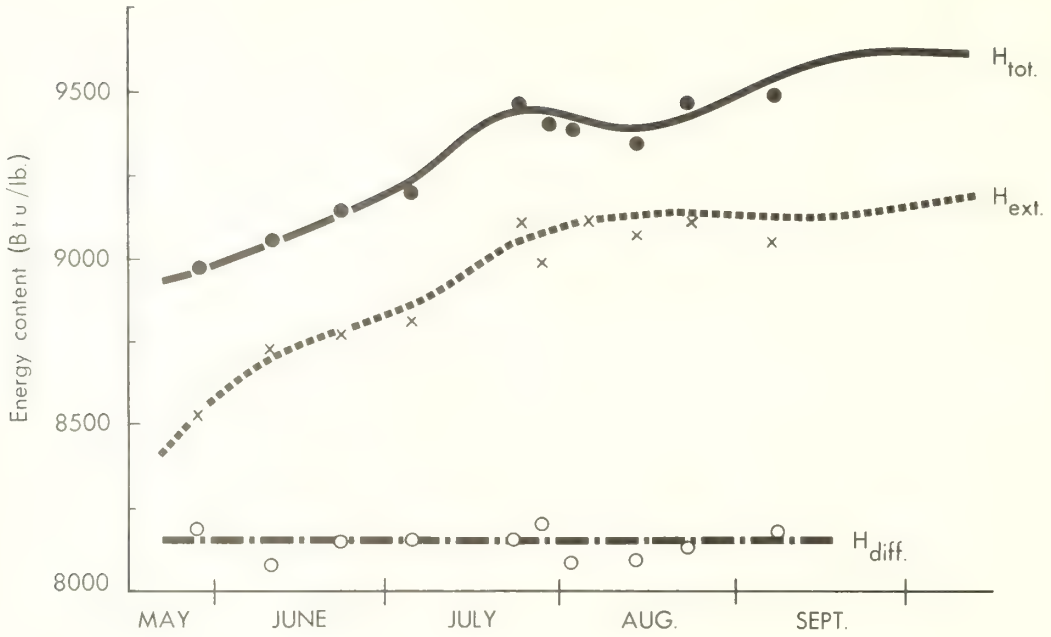

Figure 13.--The energy content of Douglas-fir needles, extracted needles, and H_{diff} during the 1968 fire season.

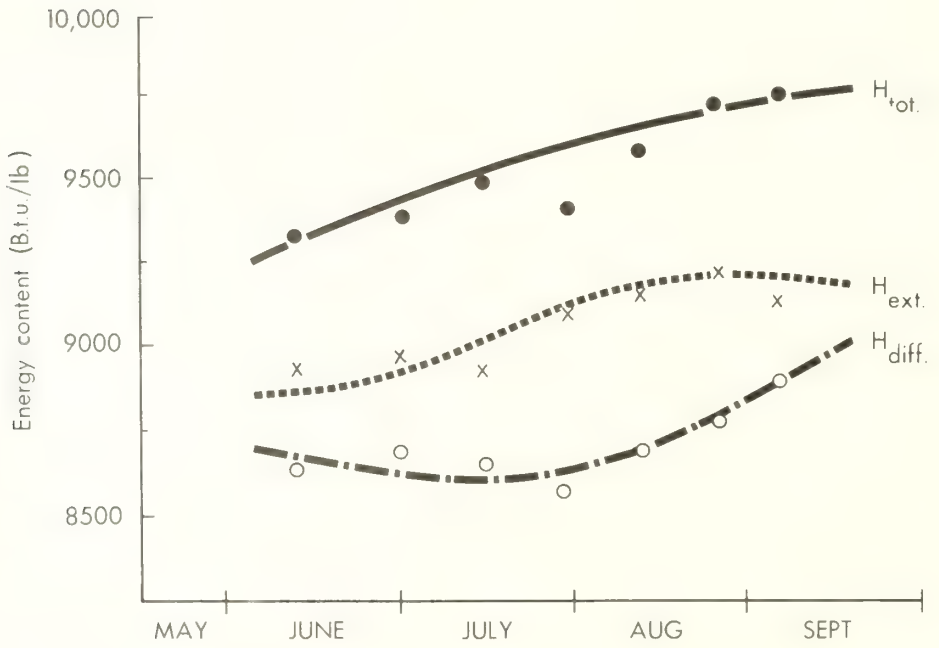

Figure 14.--The energy content of Douglas-fir needles, extracted needles, and H_{diff} during the 1969 fire season.

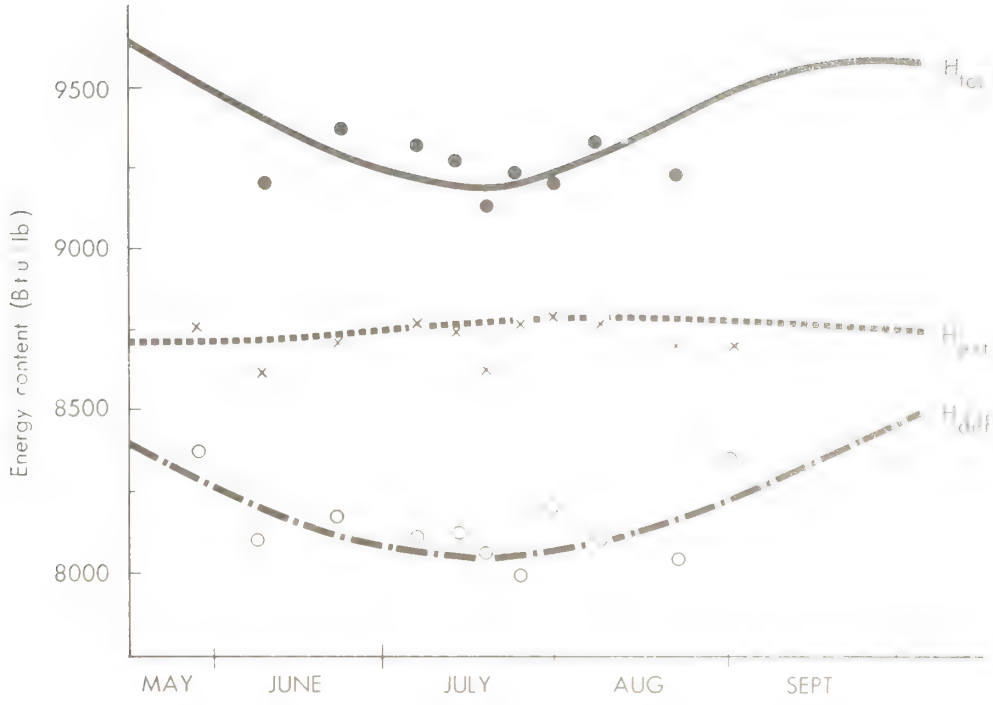

Figure 15.--The energy content of ponderosa pine needles, ether extracted needles, and H_{diff} during the 1968 fire season.

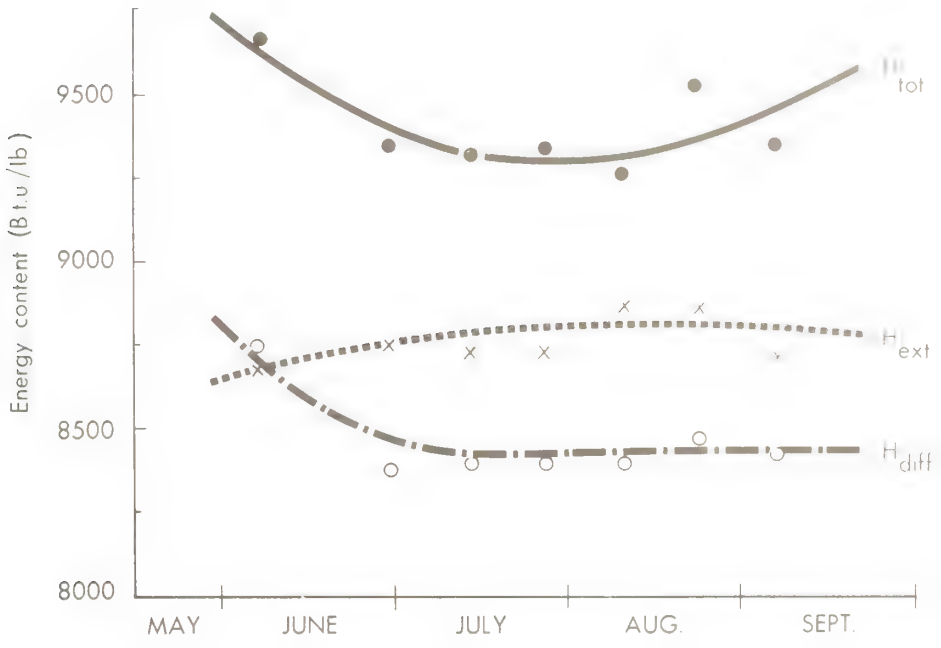

Figure 16.--The energy content of ponderosa pine needles, ether extracted needles, and H_{diff} during the 1969 fire season.

CONCLUSIONS AND DISCUSSION

The conclusions that can be made from this study are:

1. The 1- and 2-year-old needles of ponderosa pine and Douglas-fir exhibited no difference in moisture trends between 1968 and 1969. The lows for both species probably occur in winter or early spring, followed by a gradual increase during the summer. No evidence was found of a summer drying trend that could indicate a relationship between lower needle moisture and susceptibility to crown fires. The effect of new needle moisture is probably insignificant in spring because of the small mass. As this mass approaches 20-25 percent of the total foliage, the moisture content approaches that of the older needles.

2. The major change detected in ponderosa pine and Douglas-fir needles was in their ether extractive content. Generally there was a summer increase of about 100 percent for fir. The changes in pine were much smaller, although it remained relatively high throughout the fire season. The biggest gain in fir occurred in the driest year. A downward trend, corresponding to the beginning of August rains, occurred in 1968. A comparison between years is complicated by the change in sample site location.

3. The energy content of the needles of these two species was highest in the late summer. Although the energy of fir increased due to extractive increase, the energy of the extracted fuel also increased. The energy change in pine was due as much to the energy change in the extractives as it was to any increase in extractives.

These conclusions regarding crown fire potential of conifers in the northern Rocky mountains lead to interesting speculations. The extractives are probably more important than the seasonal changes in energy levels in terms of ignition and fire propagation rates. Extractives may provide a significant aspect of flame propagation within conifer crowns, and the doubling of these compounds in fir during the fire season could be important to the possibility and extent of crowning.

Another interesting possibility is that fir responds differently than pine to summer drought with regard to accumulations of extractives. Perhaps the crowning potential of pine is high for a greater portion of the year because extractives remain uniformly high, while fir is only high in crowning potential during the drier fire seasons because its extractive content varies with drought.

The seasonal energy changes of Douglas-fir and ponderosa pine foliage were only about 500 B.t.u./lb.; since this is less than 10 percent of the total energy of the needles, it would not seem too important. But when the availability of living needle energy to the combustion process is probably far less than 8,000 to 9,000 B.t.u./lb., then a gross 10-percent increase may be more meaningful. Since H_{diff} for ponderosa pine needles remained quite uniform through the season, the energy increases of fir foliage are probably of more value in the predictions of crown fires.

The importance of seasonal changes in foliar moisture to crown fires seems to need reevaluation. Actually there was little difference in moisture trends of needles between the wet 1968 season and the dry 1969 season. This difference was not tested due to the sampling site change. Mature Douglas-fir and ponderosa pine foliage increased in moisture content during each fire season. Apparently, foliar moisture content is not directly related to summer drying. Perhaps the extractives, or some portion of them, need to be considered along with moisture content in approaching the problem of crown fire susceptibility. Could it be that foliar extractives are volatilized through a steam distillation mechanism in a fire and that an increasing moisture trend enhances this combustion process within coniferous crowns? Obviously more work is needed to investigate such a possibility.

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APPENDIX

APPENDIX A

The means of moisture content for Douglas-fir needles, 1968.

Date	Code	Age 0 $\bar{X}$	Age 0 Sig.	Age 1 $\bar{X}$	Age 1 Sig.	Age 2 $\bar{X}$	Age 2 Sig.
6-10	A	95	BC	73	[1]N	70	BDEFGHIJ
6-21	B	259	ACDEFGHIJ	91	N	85	ADEFGHIJ
7-5	C	186	AB	91	N	79	DEGHIJ
7-19	D	141	B	111	N	105	ABC
7-26	E	158	B	111	N	106	ABC
8-2	F	134	B	115	N	108	ABC
8-12	G	127	B	128	N	116	ABC
8-23	H	125	B	105	N	104	ABC
9-6	I	117	B	105	N	106	ABC
11-1	J	121	B	113	N	105	ABC

[1]N = no significance from any other mean.

APPENDIX B

The means of moisture content for ponderosa pine needles, 1968

Date	Code	Age 0 $\bar{X}$	Age 0 Sig.	Age 1 $\bar{X}$	Age 1 Sig.	Age 2 $\bar{X}$	Age 2 Sig.
5-27	A	198	B	97	EGHIJKL	88	JH
6-10	B	110	ACDEFH	99	EHJL	82	EFHIJK
6-21	C	234	BIKL	94	EGHIJKL	86	HJ
7-6	D	224	BKL	108	[1]N	96	N
7-13	E	195	B	123	ABC	104	B
7-19	F	193	B	105	H	103	B
7-26	G	198	B	116	AC	102	N
8-2	H	191	B	126	ABCF	113	ABC
8-12	I	149	C	116	AC	106	B
8-23	J	155	N	120	ABC	117	ABC
9-6	K	127	CD	115	AC	105	B
11-1	L	124	CD	115	ABC	101	N

[1]N = no significance from any other mean.

APPENDIX C

The means of moisture content for Douglas-fir needles, 1969

Date	Code	Age 0 $\bar{X}$	Age 0 Sig.	Age 1 $\bar{X}$	Age 1 Sig.	Age 2 $\bar{X}$	Age 2 Sig.
6-11	A	265	BCDEFG	112	G	89	[1]N
6-30	B	180	ACDEFG	98	G	86	N
7-14	C	125	ABG	94	GE	92	N
7-28	D	125	ABG	103	G	93	N
8-11	E	137	AB	116	C	109	N
8-25	F	136	AB	108	N	99	N
9-8	G	150	ABCD	122	ABCD	96	N

[1]N = no significance from any other mean.

APPENDIX D

The means of moisture content for ponderosa pine needles, 1969

Date	Code	Age 0 $\bar{X}$	Age 0 Sig.	Age 1 $\bar{X}$	Age 1 Sig.	Age 2 $\bar{X}$	Age 2 Sig.
6-11	A	216	CDEFG	124	[1]N	81	EG
6-30	B	209	CDEFFG	95	N	83	EG
7-14	C	175	ABEFG	101	N	92	E
7-28	D	166	ADEFG	112	N	98	N
8-11	E	125	ABCD	112	N	119	ABC
8-25	F	141	ABCD	114	N	106	N
9-8	G	131	ABCD	105	N	109	AB

[1]N = no significance from any other mean.

APPENDIX E

The means of extractive content of Douglas-fir needles, 1968

Date	Code	Age 0 $\bar{X}$	Age 0 Sig.	Age 1 $\bar{X}$	Age 1 Sig.	Age 2 $\bar{X}$	Age 2 Sig.
5-27	A	[1]NS		6.5	FGHJ	7.4	GH
6-10	B	NS		5.5	FGH	6.3	EFGHIJ
6-21	C	8.6	[2]N	6.0	FGH	6.8	FGHIK
7-5	D	8.1	N	6.2	FGH	6.5	EFGHIK
7-19	E	7.6	N	7.4	N	7.7	BD
7-26	F	9.1	J	8.1	ABCD	8.5	BCD
8-2	G	9.5	J	8.0	ABCDJ	8.7	ABCDJ
8-12	H	8.5	N	8.0	ABCDJ	8.7	ABCDJ
8-23	I	7.7	N	7.7	N	8.1	BCD
9-6	J	6.9	GF	6.8	FGH	7.4	BGH
11-1	K	8.2	N	7.9	N	8.3	BCD

[1]NS = not sampled.
[2]N = No significance from any other mean.

APPENDIX F

The means of extractive content of ponderosa pine, 1968

Date	Code	Age 0 $\bar{X}$	Age 0 Sig.	Age 1 $\bar{X}$	Age 1 Sig.	Age 2 $\bar{X}$	Age 2 Sig.
5-27	A	[1]NS		10.6	DEFGJK	11.6	BCDEFGHIJKL
6-10	B	NS		9.1	[2]N	9.1	A
6-21	C	NS		9.8	N	9.2	A
7-6	D	4.7	L	9.1	A	8.2	A
7-13	E	5.4	L	8.0	A	8.8	A
7-19	F	4.8	L	7.5	A	7.6	A
7-26	G	4.9	L	7.9	A	7.9	A
8-2	H	5.1	L	8.7	N	9.0	A
8-12	I	5.3	L	8.8	N	9.0	A
8-23	J	5.4	L	7.5	A	7.9	A
9-6	K	5.4	L	7.5	A	8.0	A
11-1	L	7.9	DEFGHIJK	9.2	N	9.1	A

[1]NS = not sampled.
[2]No significance from any other mean.

APPENDIX G

The means of extractive content of Douglas-fir needles, 1969

Date	Code	Age 0 $\bar{X}$	Age 0 Sig.	Age 1 $\bar{X}$	Age 1 Sig.	Age 2 $\bar{X}$	Age 2 Sig.
6-11	A	10.4	BCDEFG	5.9	BC	6.1	BC
6-30	B	4.7	ADEFG	4.8	DEFG	4.9	DEFG
7-14	C	4.6	DEFG	4.6	ADEFG	4.7	ADEFG
7-28	D	7.6	BC	7.2	ABC	6.9	ABC
8-11	E	7.8	BC	6.6	BC	7.4	ABC
8-25	F	8.9	BC	7.8	ABC	7.9	ABCD
9-8	G	8.0	BC	7.7	ABC	7.3	ABC

APPENDIX H

The means of extractive content of ponderosa pine needles, 1969

Date	Code	Age 0 $\bar{X}$	Age 0 Sig.	Age 1 $\bar{X}$	Age 1 Sig.	Age 2 $\bar{X}$	Age 2 Sig.
6-11	A	4.9	BFG	8.4	[1]N	7.3	N
6-30	B	3.7	DEFG	7.4	N	7.2	N
7-14	C	4.2	FG	8.3	N	8.0	N
7-28	D	4.8	B	7.6	N	7.8	N
8-11	E	5.1	B	8.7	N	8.0	N
8-25	F	6.3	ABCDE	8.5	N	8.5	N
9-8	G	6.5	ABDCE	8.5	N	8.3	N

[1]N = No significance from any other mean.

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AN ANALYSIS OF RETARDANT USE

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USDA FOREST SERVICE
RESEARCH PAPER INT-103, 1971

INTERMOUNTAIN FOREST AND RANGE
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Research Paper INT-103
August 1971

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ABSTRACT

The use of chemical retardants in fire control and management is a big business that involves many dollars, many people, and much equipment. Due to a number of variables such as fuel types, fire weather, facilities, capabilities, and policy, it appeared that retardants may not always be applied as efficiently as they might be. In order to assess field practices, 90 policymakers, equipment developers, and retardant users and evaluators--primarily in the Intermountain West--were sampled in a survey to determine how and why they use retardants and to obtain suggestions for better utilization of this vital fire management tool.

An analysis of the responses from the interviewees, and of the findings from a concurrent Fire Retardant Chemical Conference, indicated that direct benefits to the retardant program would probably result from positive action in the following areas of activity: (1) Health, safety, and pollution; (2) dissemination of information; (3) clarification of policy; (4) replacement of obsolescent aircraft; (5) optimal use of helicopters; (6) field evaluation of retardant effectiveness; (7) improvement of operational procedures; (8) quality control of retardant base operations; and (9) development of improved chemical formulations.

A resumé of the development of retardant use precedes a section on current patterns of use. Cost-benefit considerations are also discussed.

PREFACE

The use of chemical retardants in fire control and management is a big business that involves many dollars, many people, and much equipment. It is a fast changing field; some of these changes can rather abruptly change the direction of the retardant program as a result of the possibilities of application, the effectiveness of the material, or the necessary delivery systems. Also, the direction of this program is definitely influenced--if not controlled--by the needs of resource managers, the availability of efficient application systems, and the specific properties of currently available chemicals.

In making this analysis, it was necessary to determine what managers expect to accomplish by the use of retardants; that is, (a) how do managers look upon such a practice, and (b) how are decisions made on when to use and how to use retardants. Also, the effectiveness of present use, and existing difficulties in the handling, delivery, and application of retardants that might influence the efficiency of such application were determined.

Although the original intent in undertaking this analysis was to take a broad look at the entire retardant program, it was found that a more coherent picture of current patterns of use could be obtained if the sampling of users was limited to some section of the country with a more or less consistent situation for optimal use. Accordingly, the actual scope of the analysis was limited generally to the areas embraced by Forest Service Regions 1, 2, 3, and 4, or more specifically the States of Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, South Dakota, Utah, and Wyoming, within which a substantial proportion of aerial retardant activity occurs. In 1967, for example, 45 percent of the slurry dropped by the Forest Service was dropped in these States.

Most of the information on current patterns of retardant use was obtained through consultation with policy makers, equipment developers, and retardant users and evaluators. Agencies contacted were the Bureau of Land Management, National Park Service, Bureau of Indian Affairs, USDA Forest Service, and various State Divisions of Forestry and aircraft contractors.

Information was obtained by personal contact, telephone, or mail. Personal contacts were informal and tailored to fit the occasion and the interviewee. Such an approach was needed in order to adjust for the interviewees' level of responsibility and experience, as well as for differences within and between agencies. However, an all-inclusive questionnaire checklist was developed for formally cataloging pertinent information, opinions, and answers immediately after the interviews. A copy of the questionnaire checklist and a roster of the 90 persons contacted are on file at the Northern Forest Fire Laboratory, Missoula, Montana.

Some information was obtained by mail and telephone because it was not always feasible to make personal contacts. In these cases, answers were sought to a list of questions, which also is on file at the Northern Forest Fire Laboratory.

Exigencies associated with the collection of information and opinion did not permit optimum sampling and scheduling of visits with interviewees. Also, the extent of information and opinion obtained from particular individuals was not always proportional to their length and breadth of experience. Thus, the sample obtained does not lend itself to statistical treatment; as a result, it is possible that some degree of subjectivity may be present in interpreting the opinions expressed.

In addition to developing the foregoing sources of information, the undertaking of this analysis provided a strong stimulus for scheduling a Fire Retardant Chemical Conference at the San Dimas (California) Equipment Development Center, September 24-27, 1968. The Conference was sponsored by the USDA Forest Service to:

(a) review what is known about retardants;
(b) analyze problems;
(c) recommend solutions; and
(d) establish a work plan for the next 3 or 4 years to accomplish certain tasks.

The discussions did not include delivery procedures. Inasmuch as the Conference resulted directly from the undertaking of this analysis, some of its recommendations are included in the "Conclusions" of this report. These Conclusions indicate potential problem areas with which fire managers and fire control specialists should be concerned.

Most of the other Conference recommendations are contained in the "Suggested Areas of Study" section in this report. These pinpoint areas of study for research and/or equipment development (individually or jointly) and management (jointly). Some of the Conference recommendations are not included because they are not germane to the scope of this analysis. However, in several areas of retardant use, the Conference's recommendations either complement or supplement the findings of this survey, and there is usually unanimity of agreement within most areas of activity.

A large share of the work that has been done in the development and improvement of equipment for the application of retardants was contributed by the user agencies, aircraft contractors, manufacturers of chemicals and equipment, universities, and private, State, and Federal research units. A major role has been played by the USDA Forest Service Equipment Centers at San Dimas, California (formerly at Arcadia) and at Missoula, Montana.

Since this analysis was begun in 1968, rapid changes in the development and use of chemical retardants have occurred. Thus, some of the material presented herein has been outdated by publishing delays: for example, the expanded use of liquid concentrates. However, many of these findings can be useful in providing a better perspective for these changes, especially to those responsible for charting new and better directions for retardant programs.

Introduction

The actual amount of retardant chemicals used annually in the United States is not known. In the spring of 1967 an estimate was made that about 16 million gallons are used every year by forest fire control agencies (75).[1] For the 1966 fire season, for example, the agencies listed below reported their actual retardant consumption as follows:[2]

	Gallons
USDA Forest Service	5,942,090
Bureau of Land Management	999,150
California Division of Forestry	3,212,600
State of Oregon	28,000
State of Washington	50,000
Southeastern States	476,320
	10,708,160

A large proportion of this amount was delivered by fixed-wing aircraft, but exact statistics are not readily available. Although the 16-million-gallon estimate was an empirical one, to rely on such an estimate would leave 5.3 million gallons unaccounted for during the 1966 season.

Similarly, the total actual cost of the retardant program is often incomplete. Units of some user agencies employ good accounting systems (36, 56, 66); some do not always segregate retardant costs from other fire protection expenditures. The major variable in the cost of retardant delivered to a fire is the distance from the retardant base to the fire. Cost estimates ranged from $0.42/gallon to $5.00/gallon. The latter estimate was primarily the result of very high aircraft guarantee and standby costs during a light fire season.

It is reasonable to assume that the current average annual cost of delivering retardant to fires by fixed-wing aircraft is somewhere between $0.50/gallon and $1.00/gallon. Also, it is quite likely that current total annual use is between 10 and 15 million gallons. Therefore, the total average annual expenditure for the retardant program in the United States is probably in the neighborhood of $10 million.

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[1] Numbers in parentheses refer to References at the end of this paper.

[2] Bureau of Indian Affairs and National Park Service obtained their supplies from one or more of the agencies listed.

Development of Retardant Use

As a rule, wood does not burn directly (5). Combustion is basically a chemical chain reaction that can be divided into three separate phases: (a) Preheating and distillation; (b) burning of volatile fractions; and (c) burning of the residual charcoal (6).

The most logical theory on how fire retardants change the pryolysis and combustion reactions for cellulosic materials is that the fire retardant chemicals lower the temperature at which pyrolysis starts. Thus, the retardants enhance the decomposition of cellulose to less flammable gases and tars, and the formation of more charcoal and water. The promotion of gradual decomposition at lower temperatures may also slightly increase the temperature at which the reaction becomes exothermic (35). Substantial progress has been made in understanding the performance of wood under fire conditions including its alteration by chemical treatment. No single theoretical analysis provides complete information to the threshold conditions of wood ignition (13).

WATER MODIFICATIONS

Water has been used for years to fight forest, brush, and grass fires. However, in rural or mountainous areas, water is frequently hard to find, or may be difficult or expensive to transport. In such situations, the big question is how to make water last longer and do a better job (63). One of the early attempts to extend the use of water resulted in treatments using wetting agents to reduce surface tension and to produce wet water. When the surface tension of water is reduced, spreading, penetrating, and foaming are increased.

Experiments in 1950 using 14 different wetting agents showed no significant differences in their effectiveness (38). This study resulted in the following conclusions: (a) Savings up to 23 percent in the volume of water required and 13 percent in time of mopup can be obtained using wet water if applied with reasonable efficiency; (b) rekindling is reduced as much as 30 percent on fires mopped up with wet water as compared with plain water; (c) foaming appears to be a desirable property of wet water in mopup because it prevents channeling of the water; (d) wet water is markedly superior to plain water in its ability to quell flames quickly, thus permitting access to an otherwise inaccessible fire; (e) dead fuels along the burning edge of a fire or along a backfire line remain wet up to 50 percent longer when sprayed with wet water

rather than with plain water; (f) fuels once treated with wet water and allowed to dry may be sprayed later with plain water with results comparable to an original spraying with wet water; and (g) most wetting agents increase the corrosive action of water, but this characteristic can be eliminated by the addition of corrosion inhibitors.

The effectiveness of water can also be improved by increasing its viscosity. Viscosity may be defined as the relative ability of a fluid to resist flow (63). Thickeners (or viscous agents) are used to increase viscosity. The principal reasons for adding a viscous agent to water are (a) to act as a sticker-spreader, and (b) to provide a thicker layer of heat-absorbing water or combustion-changing chemical.

Some thickeners tested and used with varying degrees of success are: sodium alginate (algin) (4, 68); calcium alginate gel (21); carboxymethycellulose (CMC) (22); guar gum and hydroxyethelcellulose (QP) (52); polysaccharide B-1459 (49); and Gelgard polymer (23). Such thickeners not only improve the affinity of retardants for ground fuels but also improve adhesion of the wet water to tree crowns (53). A useful working tool for measuring viscosity is the modified Marsh funnel (43).

RETARDANT CHEMICALS

Fire-retarding chemicals are generally known as either short-term or long-term retardants. Short-term retardants depend primarily on cooling action to slow fire spread and are best used in direct attack. Long-term retardants depend primarily on chemical action to slow or stop fire spread. The first long-term retardant that was widely applied on wildland fires consisted of a slurry of formulated sodium calcium borate and water; it is commonly known as borate. Although borate may be effective for many hours or days on all but the highest intensity fires, it has three major disadvantages: (a) It is toxic to plants; (b) it is very abrasive; and (c) it is mildly corrosive (10). It is no longer used, but a large segment of the general public still thinks of retardant-carrying aircraft as "borate" planes because of its original widespread use.

Borate was replaced by a swelling slurry commonly known as bentonite, which has the following advantages over borate: (a) It is easier to mix; (b) it sets up into a stable, viscous gel; (c) it is less expensive; (d) it is readily available in many locations; (e) it is less abrasive in pumps; (f) it is nontoxic to plants and animals; (g) it does not compact under prolonged storage; (h) it is noncorrosive to metals; and (i) it requires less handling than does borate. However, bentonite has two major disadvantages: (a) It is a short-term retardant; and (b) it creates slippery footing (10, 69). Thus, it too has been almost entirely replaced by more recently developed slurries.

The two chemical formulations most commonly used currently are Phos-Chek (diammonium phosphate with a guar gum derivative thickener) and Fire-Trol (ammonium sulfate with an attapulgite clay thickener). Both of these chemicals are long-term retardants that (a) coat fuels well; (b) are effective for many hours or days, depending on relative humidity and wind; and (c) are nontoxic. Both corrode, but the addition of inhibitors and good housekeeping (washing of all systems soon after use) tend to minimize corrosion. Phos-Chek is reported to be less abrasive than Fire-Trol (10, 24, 27).

To determine the location of current and previous retardant drops, coloring agents are added to the slurries. These agents perform equally well in plain water or viscous water. Pigment coloring agents need the solids of clay to do the best job.

The rapid switch in the West from borate to bentonite and then to both Phos-Chek and Fire-Trol has been phenomenal. In 1963, for example, delivery by one Forest Service region, which is a major retardant user, consisted of 42 percent borate, 31 percent bentonite, and 27 percent Phos-Chek. By 1967, this region's delivery consisted entirely of Phos-Chek and Fire-Trol (86, 89, 91, 93, 95).

Concurrent with increased use of Phos-Chek and Fire-Trol in the Western United States has been the development and use of liquid phosphate concentrates in the East (51, 82). Western users of retardants currently are showing increased interest in these liquid concentrates.

These have the following desirable characteristics: (a) No physical handling is required for unthickened solutions; (b) there is no need to store premixed solutions; (c) they are stable solutions that usually don't "settle out"; (d) they have a low freezing point; and (e) they can be mixed while they are being pumped into the aircraft.

They do have the following undesirable characteristics: (a) Some concentrates have to be diluted before coloring agents can be added; (b) unless inhibited, they corrode under some operating conditions; (c) they are more expensive than powdered chemical formulations if mobile storage tankers need to be purchased; and (d) thickeners must be added by the user (63).

An alternate possibility to slurries for wildland fire control has recently been tested by the Canadians (41). It is a backpack sprayer-duster which consists of a high-efficiency blower driven by a two-cycle, air-cooled gasoline engine. However, when tested on forest fires, this device has proved ineffective because (a) the capacity is too small (equivalent of only 4 gallons of water); and (b) the air blast from the nozzle tends to increase fire intensity within the powder-delivery range. Nevertheless, the dropping of dry chemicals instead of slurries from aircraft might be another possibility that still needs more thorough testing.

RETARDANT TESTING

A procedure for qualifying proposed new retardants has been established by the USDA Forest Service (97). This involves the following three field units of the Forest Service, each of which has specific functions assigned to it.

First, the Northern Forest Fire Laboratory at Missoula, Montana, performs tests to verify physical and chemical properties of the product (71). The product's effects on rate of spread and weight loss are also measured on mat-type fuel beds in a controlled environment (48).

Second, the Forest Service Equipment Development Center at San Dimas, California, performs operational tests to determine whether the chemical can be mixed and applied, using commercial equipment. This Center also evaluates the bulk handling and corrosion properties.

Third, the Western Forest Fire Laboratory at Riverside, California, tests the product for its retardant and suppressant effectiveness, using standard brush piles (30).

The Northern Forest Fire Laboratory currently is seeking to answer the following questions: (a) What is the optimum amount of salt required per unit of fuel or ground area? (b) What is the optimum viscosity that will permit a maximum amount of liquid to penetrate the fuel complex and cover the particles? (c) What is the minimum amount of water necessary to achieve adequate coating of fuels? (d) How can the rate of release and liquid configuration of

the retardant be controlled as it leaves the aircraft? and c) How do requirements for air application differ from requirements for ground application? (46).

In a preliminary test, this Laboratory found that retardants with the lowest viscosity appeared to be more effective in reducing rate of spread. The finding was based on wind tunnel burning tests of phosphate and sulfate retardants having the same concentration of salt, but different viscosities. This suggests that it is more important to completely coat all the fuel with the retardant than it is to apply a thick layer on part of the fuel when using a given amount of salt (47). However, it does not necessarily follow that the retardant with the lowest viscosity will be the most effective when dropped from aircraft.

POSSIBLE USES OF FOAM

The successful use of foams in extinguishing aircraft fires at airports has raised the possibilities of using foams to combat wildland fires (55). An extensive search for suitable foams has been made, particularly by the Canadians (83).

Theoretically, at least, foams would appear to hold considerable promise. A solution of 1 to 4 percent foaming agent to water can be blown mechanically to between 200 and 1,000 times its original volume. Some foams insulate forest fuels from the intense radiant heat that spreads fires. This allows moisture to drain from the dissipating foam at a rate that permits the moisture to be absorbed by many of these fuels (58). Also, combustion inhibiting chemicals, such as the ammonium phosphates, can be added to some solutions without seriously reducing expansion property of the foam.

Actual tests by ground generators and by aircraft drops have been disappointing. Tests with ground applications have shown that slash protruding from the mass of a foam line will carry fire and that the effectiveness of a foam line is limited by the duration of its wetting ability, windspeeds in excess of 5 m.p.h., and high temperatures (57).

Both low-expansion and high-expansion foams tested in drops from aerial tankers were found to be generally unstable, even when used with thickening agents. Drops did not penetrate dense cover types, and considerable drift and dissipation were experienced in light winds. Therefore, the use of foaming agents in firefighting chemicals dropped from aerial tankers does not seem promising. However, foaming can occur in a free-falling liquid drop from a tanker, and new evaluations may be desirable when further improvements in foam concentrates are made (15).

DELIVERY BY FIXED-WING AIRCRAFT

The development of techniques and equipment for effective free-dropping, or cascading, of water and chemical slurries marks a major advance in aerial firefighting. In the United States, agricultural spraying and dusting aircraft were first adapted for this purpose. The demand for speed and greater volume soon led to use of larger World War II surplus bomber aircraft. In many parts of Canada, the availability of numerous lakes and rivers permitted use of water-based air tankers fitted with scoop tanks.

Widespread interest in air tankers resulted from water drop tests conducted during 1955 on the Mendocino National Forest in California. The aircraft used were converted Stearman N3N's operated by agricultural spray pilots on contract. The key to success was discarding spray equipment in favor of a quick release of the entire tank contents. They carried about 120 gallons (7, 55).

Late in 1956, the Forest Service converted Navy TBM's into air tankers. These were modified to increase their load capacity to 600 gallons. In addition, private contractors were modifying other surplus military aircraft, including F7f's, B-25's, PB4Y-2's, B-17's, and B26's. Their capacities ranged from 1,200 to 6,000 gallons (76).

Although the concept of quick-discharge, large door or gate release of the entire content of a tank was a vast improvement over agricultural spraying methods, the search has continued for better gating devices to improve patterns of water (and retardant) drops (39). One such improvement has been the installation of dual (in TBM's) or multiple (in B-17's, B-26's, and PB4Y-2's) tanks to permit the release of slurry in train rather than in salvo. Recent development of electronic timing devices has resulted in a wide choice of pattern preferences with considerable precision in the drops made from larger planes.

Tests of airdrops using retardant slurry conducted between 1955 and 1959 showed that (a) viscosity reduces drift, (b) drift increases with both height and speed, (c) big gates give better controlled drops, and (d) advantages of large carrying capacity versus maneuverability depends on the fire situation (17). Other tests during 1967 in Canada, using both water and slurry, showed somewhat similar results (59).

Firefighting experience has provided clues to the drop pattern expected according to the following variables: (a) Kind of aircraft and retardant used; (b) drop method; (c) weather conditions; and (d) terrain features (92). However, controlled tests of retardant drops on actual fires would provide the best method of determining air tanker productivity. This type of study could be expensive. Evaluation is also needed on the combined and separate effects of air attack, hand crews, and ground equipment on efficient wildfire containment (80).

Although most approved retardants contain corrosion inhibitors, corrosion still occurs, particularly on exposed portions of the aircraft, including tanks, gates, and related fittings. It occurs if (a) the slurry is not mixed properly, thereby reducing the amount of corrosion inhibitor; (b) different metals are used in the aircraft components than were used in testing for corrosion; or (c) housekeeping is poor. A number of recommendations have been made that should help minimize corrosion (26, 88).

A key factor in the successful application of retardants from the air is good communications between air and ground forces, particularly in the early stages of a fire. One way to achieve this is to provide initial attack pilots with both agency and air net radios, but this has seldom been done. An improvision that may help fill this need has recently been described by Zamora (103). Called the Lincoln harness, it was devised to fill the need for an inexpensive method of simultaneously monitoring Air Net and Forest frequencies and instantly communicating to either while on air observation.

Experience has shown that air tankers carrying fire retardants can be effectively used for (a) holding action on small fires; (b) tactical air support to line crews; and (c) pretreatment or indirect attack.

Air application of fire retardants is usually ineffective (a) on fast-moving fire in heavy brush or timber, (b) in winds above 30 m.p.h., (c) on targets located in the bottom of steep, narrow canyons, (d) under smoky conditions where visibility is less than three-fourths mile, (e) when radio communication is inadequate to coordinate air tankers, and (f) when drops of less than 100 gallons are made at 80 m.p.h. or from more than 100 feet above the target (98).

In view of the foregoing opportunities and limitations, some of the factors which should be considered in assessing the need for dispatching air tankers are (a) fire situation, (b) resource values (in most areas), (c) fire-danger rating, (d) weather forecast, (e) expected time of arrival of ground crews, (f) total fire control workload, (g) time of day, (h) aircraft availability, (i) flight time from retardant base to fire, and (j) evaluation of the need for additional drops depending on the changing fire condition (11, 14).

Although the aerial application of retardants can be tremendously effective in certain situations, maximum benefits can only be obtained through coordination with ground forces (74). In regard to coordination with smokejumpers, the buying of time is one of the major reasons for their deployment, as well as for the aerial delivery of retardant. In some situations, smokejumpers are now considered with all other facilities, and ordered if they can be first to reach a fire, even if the fire is near a road (3). Thus this shift in emphasis on their use will probably have some effect on air tanker use.

The World War II bombers have done an admirable job in serving as air tankers for retardant delivery. However, at the present rate of attrition and without adequate replacement, it is expected that the tanker fleet will be drastically reduced in the next few years (99).

The substitution of newer aircraft, preferably of the V/STOL class, such as the de Haviland Twin Otter (12, 101), will pose a tremendous problem for contractors because of cost and availability. One apparently feasible solution would be the shifting of aircraft around the country according to the seasonal variations in fire behavior patterns in different areas (72).

A major difficulty in the interagency use of air tankers for initial attack is their optimal use by the involved user agencies, regardless of the apparent needs of the dispatching agency (102). Unfortunately, when severe fire weather and particular fire-complex situations occur simultaneously, all of the cooperators are often caught in the same bind in their urgent need for air tankers.

APPLICATION BY HELICOPTERS

To date, helicopters have been used primarily to transport men, supplies, and equipment, and for scouting (9). However, a helicopter weighing 10,000 to 12,000 pounds was reported to be the most efficient aircraft for transporting water in eastern Canada (106). Also, the Russians have devised a water bombing technique using an Mi-6 helicopter (2). Other tests in California have shown that under some conditions the ground coverage obtained with retardants dropped from helicopters using tanks was comparable to the coverage obtained using small fixed-wing aircraft (18).

There are three major deterrents to the use of helicopters in transporting retardants: (a) Cost, (b) corrosion, and (c) size. On one fire in 1968 that straddled a river, a Sikorsky S-61 helicopter was used for hauling water. This was a turbine-powered jet aircraft with a capacity of 900 gallons. A total of 54,000 gallons was dropped on the fire in 3 hours; during one short period, five drops were made in 7 minutes. At that rate, the potential total output would be 38,000 gallons of water per hour. The charge for the machine was $1,200 per hour. Although the relatively high cost of helicopters (compared with fixed-wing aircraft) is a major deterrent to their use, the quick turnaround time in this particular case more than offset the high hourly cost.

A second deterrent to greater use of helicopters for dropping retardants is the possibility that certain fire retardants will corrode aircraft and cause structural failure or engine damage. However, studies using fluorescent dye as a tracer showed that little or no retardant reaches the helicopter under most conditions. The helicopters studied were the Bell 47G and Hiller 12E (25). These findings have not yet been fully accepted.

The third major deterrent to helicopter use has been the relatively smaller carrying capacity of some models. Tests of a Bell 204B helicopter equipped with a 360-gallon tank showed that the tank discharged too slowly (87). Performance was improved when the same ship was equipped with a 300-gallon tank modified with a sloping deck and dual doors (90). Field tests in Oregon of drop patterns from two large helicopters showed that the tanks used with a Kaman H-43A gave small area coverage compared to the size of the helicopter and patterns made with other helicopters. On the other hand, the Sikorsky S-58 with a monsoon bucket gave more area coverage, but the bucket itself was needlessly heavy (34).

An improved fiber glass bucket recently has been developed that is not only lightweight but also resists corrosion. In addition, the bucket is sling-mounted to keep the retardant away from the helicopter. (However, there is resistance to this in California because of the instability created by the swinging bucket.) The bucket is being manufactured in three sizes: 140-, 450-, and 1,000-gallon capacity (64, 79). Another recent development is a portable retardant supply system designed to decrease the turnaround time for helicopters (65).

Although the use of helicopters in delivering retardant does have its limitations, certain inherent advantages can be enhanced when they are used in combination with air tankers in ferrying firefighters to and from the fireline and in delivering supplies to ground crews. On at least one recent fire, a fully integrated helitanker-air tanker attack materially contributed to the control of a fire in a safe, effective maneuver because proper communications were maintained between the aircraft pilots, air attack bosses, and the helicopter manager (54).

Greater use of helicopters in fire control and resource management may hinge upon the outlook for contractors. In the long run, the following trends should work in their favor:

(a) The steadily growing congestion of all forms of surface transportation;

(b) the technological developments that are improving the helicopter and its operating economics; and

(c) increasing public acceptance (42).

In the meantime, the following are needed if full advantage is to be taken of the opportunities offered by helicopters:

(a) Establishment of a cost-benefit relationship by a qualified economist;

(b) an analysis of optimum helicopter deployment for initial attack;

(c) design of a helicopter specifically for fire suppression work;

(d) research to determine the optimum viscosity of fire retardants for helicopter delivery;

(e) the development of an effective quickie-type retardant that will eliminate the mixing process;

(f) the development of smoothly-functioning interagency coordination; and

(g) full recognition that the individual decisionmaker will make or break the success of helicopter operations on the fireline (78).

GROUND APPLICATION

The application of retardants by ground tankers, or other ground-oriented dispensing devices, has also lagged behind application by fixed-wing aircraft. Four of the major fire protection activities in which ground devices appear to hold considerable promise are (a) wildfire suppression, (b) fuel hazard reduction along roads, (c) prescribed burning, and (d) fireproofing of campground areas.

Tests by the Oregon Department of Forestry using viscous water (alginated water), calcium alginate gel, and viscous diammonium phosphate showed that all of these fire-retarding materials were superior to plain water. However, no practical operational system was ever developed for the alginates because of problems in mixing, storage, and equipment maintenance (62). In California, limited use has been made of a demand mixer for viscous water and a portable batch mixer for viscous diammonium phosphate.

Although some fire crews have found ground application of retardants to be worth the time and money and are continuing to increase such use, other crews have discontinued ground application altogether (19). Several of the Bureau of Land Management's districts have had varying degrees of success using ground tankers, principally in the grass-pine-sagebrush types.

The Forest Service's Equipment Development Center at Missoula has developed a 1,000-gallon tanker that can be mounted on skids or trailers; it has a spraying capacity of 5,000 square feet per minute. The tanker has been used successfully in treating the perimeters of 10-acre prescribed burn study areas on the Flathead National Forest in Montana. Its principal advantages are the speed and uniformity of retardant application.

In the palmetto-gallberry and wiregrass fuels of the southeastern United States, a chemical control line 30 feet wide was made using a ground tanker pumping a 15-percent solution of diammonium phosphate. Strip head fires of variable width, depending upon the burning conditions, were set and permitted to run into the chemical line where the fire was extinguished. These strips burned out quickly; thus the width of the control line was extended several hundred feet in a very few minutes (50).

The principle of using large tankers with high output pumps appears to be an effective fire control measure. However, there remains the job of improving application in various fuel types and under various weather conditions, and of establishing limitations for use of such tankers and pumps (31).

It was recently suggested that heavy plastic can be used with a siphon pipe and valve to convert a pickup truck into an improvised tanker (45). Coated fabric tanks are also available for this purpose (40).

Methods for economically fireproofing roadsides have been generally unsuccessful to date, particularly in areas with highly flammable fuels and large volumes of traffic. However, the same chemicals that are used for other fire protection measures might also be effective in such areas (70).

Chemicals applied should remain insoluble throughout the fire season (29). In a recent test, flame-retardant inorganic salts were encapsulated to prevent them from being dissolved by rainfall (81). This prevented leaching of the salt. However, when the encapsulated salts were applied to a fuel bed and tested in a wind tunnel, their retarding ability was almost totally ineffective because the flames advanced between the particles of retardant (46).

In another study, emulsions of water-insoluble phosphorus containing polymers were applied to a fuel bed. These coated each needle with flame-retardant resin that adhered as a water-resistant, flameproofing coat after drying (81). Recent field tests in California using Flame-X Brush Spray have shown that this commercial retardant is effective after more than one-third of an inch of rain has fallen (32). However, this product was not effective following a laboratory-simulated 1/2-inch rainfall at the Southern Forest Fire Laboratory.

Tanker application of retardants in prescribed burning is increasing. One study on the use of diammonium phosphate by ground tankers in California had three objectives: (a) Determine this treatment's effectiveness in protecting adjacent forest vegetation from ignition by radiation and spot fires, (b) determine its effect on the rate of spread within the broadcast burn area, and (c) determine the practicability of using such equipment for treating slash and adjacent exposed areas. Less than one-third as many spot fires started in the sprayed portions of the study areas as in the unsprayed, and fires that did start smoldered and were not difficult to control (94).

Moreover, the fire's rate of spread within lightly treated areas was one-tenth of that in unsprayed areas. In spite of this reduction in burning rate, more treated fuel was eventually consumed than in similar, but untreated adjacent fuel.

The 300-gallon batch mixer that was used proved to be a capable and versatile piece of fire-fighting apparatus (33).

SAFETY

The use of retardants presents some hazards that are sometimes major factors in deciding which retardants to use and how to use them. Slipperiness, for example, can be a great hazard in some situations and was one of the reasons for discontinuing the use of bentonite (8). The dust that occurs when sacks of ammonium compounds are broken open can be irritating to respiratory systems and to the eyes. During windy weather, mixing crews often find it necessary to wear face masks. This has been one of the major factors that has led to the establishment of bulk storage plants or the use of liquid concentrates.

In ground application, the ammonia from retardants may be irritating to nozzle operators. Retardants that are irritating to the skin or that might cause allergies are not approved for use.

Vortex turbulence from large or heavily loaded, fixed-winged aircraft flying low and slow can be a hazard in some situations. These horizontal whirlwinds having velocities of up to 25 m.p.h. can cause sudden and violent changes in fire behavior in patchy fuels on calm days (20). The rotor wash from helicopters can have the same effect (77), which is one of the reasons for their limited use in retardant applications.

Retardant drops from air tankers of any capacity can be hazardous to ground personnel (84). Also, the effects of the various retardants might result in pollution to the environment in some areas.

Current Patterns of Retardant Use

The ways in which retardants are used vary throughout the Rocky Mountain West. These differences reflect the existence, or absence, of firm policy and the degree of policy acceptance on the part of retardant users. The major reasons for inconsistent and varied policies are: (a) Differences in fuels, hazards, risks, resource value classes, etc., between field units; and (b) differences between fires; that is, a general feeling that there are no two fires exactly alike from the standpoint of initial suppression action required.

Several reasons were given for the absence of a firm policy: (a) Undecided on what unit policy should be; (b) supervising unit not yet aware of the full potential of retardant use; (c) higher level guidelines are considered adequate; (d) have to depend on another agency to dispatch retardant, therefore no point in developing unit policy; (e) want to accumulate more experience; (f) major emphasis is on ground and helitack crews, therefore no need for policy on retardant use; (g) retardant program and other air operations are underfinanced so a firm policy would serve no useful purpose because it couldn't be followed anyway; (h) no need for a firm policy because air tankers are always available from other subunits; (i) the major unit leaves policy formulation up to each subunit but the subunits don't quite get around to developing policy for their respective subunits; and (j) a feeling that if firm policies are developed, they might be followed too literally as a substitute for sound judgement.

In lieu of concise policy, unit "philosophies" are frequently expressed through written guidelines on when (or when not) to use retardant, or by verbal admonishments during pre-season training sessions. These mediums of expression naturally leave considerable room for

various interpretations. On the one hand, they result in flexibility, which is often good; on the other hand, they may result in improper use, which is not good.

Within the Forest Service, policy (or guidelines) may be documented in the Forest mobilization plan, Forest dispatching plan, Forest fire plan, equivalent District plans, manning and specific action guides, or by an attachment on an approved automatic dispatching map. Thus a person transferring from one unit to another during the fire season could encounter difficulty in trying to determine the policy of the new unit. Policy documentation for non-Forest Service agencies is similarly, though not so widely, scattered.

Usually, if the major unit has not established a firm policy, neither will the subunits. A general feeling prevailed among the various user agencies that subunits would probably be able to issue workable guidelines if firm policies were established at the top level.

Even after policies (on retardant use) have been established, restrictions on their implementation are often encountered. In some cases, subunits may either misinterpret policy or may actually be reluctant to follow policy. The most common reason for the latter was that the subordinate did not agree with the policy established at a higher level. In many cases, lack of qualified personnel or adequate financing, particularly for obtaining larger fixed-wing aircraft and better retardant bases, were limiting factors.

One unusual situation recounted was a case where a subunit drastically reduced its burned acreage primarily through the use of retardants. As a result, it was considered to be an "asbestos" subunit and experienced great difficulty in obtaining sufficient financing for a retardant program adequate to meet policy requirements on burned acreage.

Deviations from policy (as contrasted with restrictions on implementation of policy) were generally less frequent. Much of this stems from the fact that in many cases there was no firm policy to deviate from. Generally, however, this would indicate that where there were firm policies they usually were appropriate or that subunit personnel were usually obedient. Local needs sometimes cause deviations in policy, or perhaps the "panic button" is pushed during a hot fire without considering policy and prudent practice. Also, there is still a rather strong tendency for some users to waste retardant on large fires.

AUTOMATIC DISPATCH

Automatic dispatching may be defined as the immediate sending of various firefighting facilities to uncontrolled wildfires in particular areas according to predetermined combinations of resource value, hazard, and fire-danger rating. There is a wide range of opinion on the desirability of automatic dispatch. In some areas, it is felt that the establishment of retardant bases cannot be justified unless automatic dispatch is the primary objective. At the other extreme, automatic dispatch is considered a threat to safety. Some of the objections expressed are the result of unclear terminology--the terms "immediate" or "preplanned" dispatch being much preferred. Nevertheless, as resource values, risks, and hazards continue to increase, the trend is toward more automatic dispatch, whatever its designation may be.

Apparently, some unit managers are not quite sure whether or not some of their subunits are on automatic dispatch. This means that preplanning and the establishment of an automatic dispatching system do not necessarily insure that retardant aircraft will be automatically dispatched. Preplanning, in some cases, may show that automatic dispatching is not feasible or desirable. Some agencies would like to have automatic dispatching, but can't afford it under present methods of financing presuppression measures.

The determination of resource values is a key to automatic dispatch in most areas. However, among units that have adopted automatic dispatching, some managers are reluctant to include sufficient area within the automatic dispatch zone.

An apparent incongruity is that nearly all retardant users recognize the value of speedy initial attack, yet automatic dispatch is anathema to some. The expansion of intraagency and interagency collaboration in automatic dispatching is badly needed.

In some situations, where automatic dispatch has been formally established, only one air tanker is immediately available. Also bombers that are needed by an agency are sometimes not available because they are already being used by the dispatching or contracting agency(ies). This raises the question of whether these units are really geared to automatic dispatch.

Another aspect of preplanning, from which automatic dispatch is derived, is preattack planning. One example is the preselection of natural barriers for burning out in deep, rocky terrain. Interest in preattack planning is rapidly increasing, and it would seem that the judicious use of retardants, whether delivered by air or ground, should be an integral part of such planning.

TACTICAL OBJECTIVES

The great variation in policy naturally results in a considerable variation in attitude toward retardant use--from automatic dispatch at the slightest hint of trouble to use only as a last resort or not at all. However, there is a strong consensus that the primary benefits of aerial retardant delivery are gained during the initial attack phase. Again, there is variation in just what this means--from very strong emphasis on automatic dispatch to waiting until a reported fire has been verified and reconnoitered.

When the latter procedure is followed, the use of aerial retardant drops may actually be followup action rather than initial attack. Practice does not always follow the usually narrow and unclear definition of "initial attack," which is another term for the term "first attack" that is defined as "The first suppression work on a fire." (USDA Forest Service Handbook 5109.12, June 1966.)

A thought-provoking idea expounded by one highly knowledgeable retardant user was that the need for adequate volume in quick succession is at least as important, and in many cases, even more important than the initial getaway time. In other words, without downgrading the importance of time, perhaps size and number of tankers available should be given greater weight for initial attack purposes.

Approximately one-half of the time, delaying fire spread is the primary tactical objective. Sometimes, line building for direct attack is the primary tactical objective, but more frequently it is the secondary tactical objective. This would indicate that the primary strategic objective may be a holding action; different tactics are used to achieve this goal.

Although the target selected is usually determined by the fire situation at the time of the drop, strong differences of opinion existed as to whether the best targets were the head or flank of the fire, or whether building an indirect line ahead of the fire would be most effective. Also, because heavy dependence is normally placed on the initial attack pilot (or someone else in the air) for selecting targets, training in fighting wildfires on the ground, or closehand observation of wildfires from the ground, should be mandatory for aircraft crews. Better communications between the ground and air are considered essential. Many contacted emphasized the need for a qualified air attack boss to serve as lead plane observer.

Preferences varied as to kinds of retardant drop patterns that should be used. A plurality was reluctant to state their preference because situations vary from fire to fire. An inverted V (∧) is often laid across the head of the fire (half in and half out) in an attempt to box in the fire head itself. Some prefer to lay the retardant parallel to the fire front and upslope from it; others try to encompass the fire completely. Slope, topography, and fuels are important considerations. There was little preference for attempting to douse the fire directly. In other words, indirect attack is usually preferred to direct attack.

Long, narrow trains of slurry are preferred on fast-moving, grass-brush fires occurring on a wide front, but salvo drops are needed for fires in dense canopies. Also, it is highly desirable to have a pattern that is long enough to cover a wide front, but wide enough to prevent the fire from spotting over (jumping) the retardant line. One problem that must be solved is how to penetrate a dense canopy to stop a fast-moving ground fire on a wide front.

When policy varies between agencies, considerable confusion can result on interagency fires. Although policies generally seem to favor initial attack as the best use of retardant, some units often used it more on followup than on initial attack. This anomaly in policy occurs when (a) the policy is ambiguous, (b) adherence to the policy results in such hesitant dispatch that retardant use becomes followup action on the fire rather than initial attack, or (c) the line which separates initial attack from followup is indistinct. Actually, situations occur in which retardant drops are very effective in followup, such as cooling spot fires and hot spots on or near the line, or reinforcing weak lines. Considerable emphasis in stated policy was given the use of retardant on followup only when there is a sure chance of effective use.

Also, there was almost unanimous expression that retardant should not be used on followup when the fire is out of control. This policy was not followed for good reason on the Caribou Creek Fire in northern Idaho during 1967. The fire started between the Trapper Peak and Sundance Fires, and had the potential of being equally, if not more, disastrous than either of these fires. The fire was already out of control and crowning when retardant was first dropped. However, a large air fleet was available to deliver large quantities of retardant, and the fire was stopped. This action occurred on September 3, 1967, and involved 11 aircraft--eight TBM's and three B-17's. During a 4- to 6-hour period, 39,200 gallons of diammonium phosphate were dropped, and the fire was controlled at 50 acres. In this case, the use of retardant on followup was justified.

Early morning drops are a powerful strategic tool that have been largely overlooked in developing policy for followup action. Although such drops offer many advantages, their use might be limited by obscurement of targets due to low-lying smoke and expenditure of pilot hours that may be needed later in the day.

The prevailing policy is not to use retardants during mopup. However, there are some important exceptions, such as when water is unavailable, or when it is necessary to extinguish "breakouts" after the fire has been contained or controlled. With regard to the latter, whether or not the retardant is being used on "mopup" usually hinges on what "contained" and "controlled" mean to the retardant user. Generally speaking, if the term "contained" is used, this usually means that the suppression action taken consists of followup. On the other hand, if the term "controlled" is used, this usually means that suppression action consists of mopup.

A major reason for declining to authorize retardant use on mopup is a general feeling that the persons doing the mopup might tend to look upon currently used chemical slurries as suppressants rather than retardants. Some field studies have found that diammonium phosphate

enhances wood consumption in addition to reducing flaming combustion and rate of spread, but these findings have not yet been confirmed by laboratory tests. Also, significantly, none of the people contacted have observed this phenomenon. If there are, in fact, fire-retarding chemicals that can safely enhance wood consumption while inhibiting flaming combustion, it would seem that the prospects for more efficient mopup (and prescribed burning) would be greatly improved. Thus this impasse needs to be resolved.

Operational procedures for the use of retardants vary between units, and reflect differences in policy or the application of such policy. Some examples are (a) a tendency to wait for confirmed reports of wildfires before dispatching retardants, (b) the employment of aggressive initial attack coupled with the stopping of retardant drops as soon as it becomes apparent that they no longer serve a useful purpose, (c) variation in operational procedure between subunits depending on actual fire situations, (d) exclusive use of retardant for initial attack versus little use for such action, (e) a request for retardant planes only when ground forces can't hold the fire, and (f) restrictions on the options available because of financial limitations. Some of these differences could probably be rectified by more specific guidelines for retardant use.

Some felt that in many cases small fires (10 acres or less) had been contained by the prompt, efficient application of retardant. Also, there was a general concensus that some fires could have positively been held to small size if more retardant had been dropped at the right time at the right place. An oft-repeated statement was that the containment of just one small, potentially disastrous fire more than justified the entire cost of the retardant program at a base for an entire year, if not for several years.

MIXING, HANDLING, AND STORAGE

Users are generally well satisfied with the retarding capabilities of Phos-Check and Fire-Trol and are almost unanimously agreed that they are more effective than bentonite and earlier materials in retarding wildfires. Little difference has been observed between the two in their retarding capabilities. However, users differ considerably in their opinion of which of the two is better from the standpoint of mixing, handling, and storage.

The decision on which retardant to use is sometimes influenced by salesmen. Some suggested that the user agencies should determine the chemical characteristics and qualities desired and then solicit bids to meet the required specifications. There was also a general feeling that a research agency should undertake the job of developing the needed specifications.

Most user agencies mix their own retardant. When mixing is done by the contractor, the problems of recruiting and holding a stable mixing crew are avoided, but the user agency usually still has to furnish the dry chemical. Also, control over viscosity, salt content, and availability when needed may be lost. In spite of the frequent turnover in mixing crews, current mixing operations generally run smoothly. However, the introduction of new chemicals (liquid concentrates, for example) would require a realignment of retardant base operations. Operations research may be needed for planning retardant base systems that include demand mixing and bulk storage facilities.

Portable mixing plants operated by experienced crews have considerable potential. However, this potential is a long way from being utilized. It does not appear to be feasible or desirable for every potential receiving unit to have an experienced crew capable of setting up and operating a portable mixing plant. Rather, the unit that furnishes the plant should also furnish the crew.

Simplified terminology would create better understanding of the nature of the chemicals used; this would result in more exact mixing and application. Mixmasters and suppression crew foremen, particularly, desire to know what the terms viscosity, centipoise, salt content, etc., mean.

There are many problems connected with the handling of dry chemicals in sacks, such as extra handling by men and machines, split sacks, wet sacks, and accountability. There is an obvious need for bulk storage and premeasured mixing quantities, but there is definite reluctance to such change. The principal reasons for this reluctance are high cost and a feeling that the recent fast changes in chemicals used are likely to continue, thus leaving plant managers with obsolete handling, mixing, and storing equipment on hand.

There is also a need for consistent, frequent measurement of viscosity and salt content. If mixing is done by a contractor, it is imperative that such measurement standards be included in the contract and checked frequently by the contracting agency.

The capacity for storing slurry at retardant bases is quite variable. At some bases the storage capacity is so low that it limits the number of drops that can be made.

An assured water supply is a critical necessity at all bases. Water sources vary considerably both in type and availability. They include tap facilities, irrigation systems, and wells. Streams, ponds, and lakes have also been used as sources of water that must sometimes be hauled for long distances.

In view of the difficulties that may be encountered in obtaining an assured water supply, there appears to be opportunities for developing a substitute for water as a carrier. Preferably, this substitute would not have the bulk or weight of water.

Retardant characteristics that users would most like to have improved are storage and delivery bulk, corrosiveness, solubility (initial and prolonged), and viscosity (retention and control). Retardant users would also like a material that is thick enough so it doesn't drift, but thin enough to penetrate clear to ground. They are curious about the possibility of using gas or dust to avoid the bulk of water and feel that experience gained in agricultural dusting and spraying and in forest pest control should be applied to retardants used in controlling wild land fires.

Generally, there is a strong desire for more rapid, widespread dissemination of information on experience with new chemicals: for example, information as to what uses are being made of liquid concentrates in the East, and what are the opportunities for extending such uses to other geographical areas?

Opinion differed considerably on whether it was necessary, desirable, or feasible to store slurries of more than one chemical, salt content, and/or viscosity at a particular base. Therefore, further exploration of this subject could provide some very useful guidelines. In one of the few cases where more than one chemical solution was stored at a base, the purpose was to "spread the business around" rather than to take advantage of the relative retarding abilities, if any.

A few instances were mentioned where retardant actually suppressed a small fire. However, none of the persons contacted consider retardants to be suppressants, nor was much

interest expressed in developing a chemical that could be depended on to act as a complete suppressant, probably because the idea of chemicals as suppressants has not yet been widely accepted. Ground followup is invariably made on all wildfires on which retardants are dropped. Nevertheless, the development of a chemical suppressant might be a desirable objective.

DELIVERY BY AIRCRAFT

Opinions varied as to how long aircraft now being used will last. Nearly all of the current air tankers are of World War II vintage and replacement parts are becoming increasingly difficult to procure. A decision will have to be made soon on what kind of ships should replace these older planes.

TBM's are generally preferred when the turnaround time is short, but larger planes are preferred for longer distances. Although the B-17 is generally as maneuverable as the TBM, more time is needed to execute the maneuvers. Sometimes, overemphasis on the economics of using TBM's on small fires having quick turnaround time has clouded the advantages of using other planes. Quite often the most efficient use of air tankers is as one arm of a three-pronged attack system that consists of air tankers, ground tankers, and helitack crews. A better selection of plane types is often needed at particular bases.

The current trend in desired fixed-wing aircraft is toward larger planes. Some even advocate planes having capacities of 8,000 to 10,000 gallons, or larger. Apparently, the main restrictions on wider use of larger planes is that they aren't available or are too expensive. It would appear that the best bet for the future would be a large, fast plane equipped with variable tank gate openings, that could hover over a fire. Turbine powered V/STOL-type aircraft, like the Twin Otter, appear promising for future use.

On the other hand, some feel that the Government should underwrite modification of available military aircraft rather than strive for new aircraft development.

The expressed need for lead planes varied from none to mandatory; the majority felt that they are very desirable to have, if available. However, opinion differed on the exact role of lead planes, and as to whether they should actually "lead" air tankers in. Also, opinions differed as to whether the air attack boss (who may be the observer in the lead plane) should be primarily a ground firefighter or an airman. Lead planes may not be needed as much for larger air tankers as for the smaller air tankers.

As initial attack pilots gain more experience, they become more proficient. This proficiency has perhaps reduced the need of lead planes. However, some feel that lead planes are needed on every drop and that the lead plane should be fast or maneuverable enough for the pilot or observer to size up the entire fire situation and to determine approaches for drops well in advance of the air tankers. Thus loaded air tankers would only make one pass to drop their load on the fire.

There is a considerable need between agencies for understanding the respective operational procedures, particularly at the local level.

Opinions on dispersal methods generally were rather vague. Long, narrow trains are desired on fast-moving grass-brush fires on a wide front; heavy salvos in dense timber. A difficult situation occurs on a fast-moving, wide-front ground fire under a dense timber canopy. The use of time bombs or similar devices for penetrating canopies and getting at the fire on the ground is not favored, probably because of the safety factor.

Variability is the primary desire in retardant dispersal. This can be achieved through different drop patterns, viscosities, and salt contents. For steep slopes a continuous train is needed, regardless of dips in rough terrain.

More than half of the persons contacted personally didn't have suggestions for improving dispersal methods; those who did emphasized the need for variable, instant gate openings fully synchronized with plane speed and height above canopy. Such gating devices should not be so sophisticated as to exceed pilot capabilities.

Another need is improved techniques for concentrating salvos. Current modifications in use include snorkels on helicopters, wire mesh to slow up rate of release, and stationary lips for longer trains.

Improved gating devices for dispensing retardant from fixed-wing aircraft have been sought for a number of years, but little has been accomplished. A B-17 at the Boise Interagency Fire Center and a PB4Y-2 at Aerial Aviation, Inc., Greybull, Wyoming, have been equipped with electronic controls that permit the continuous discharge of all eight tanks in sequence or in various combinations. Such controls increase the versatility of retardant dispersal. The manufacturer of the Twin Otter is currently fitting a craft with retardant tanks.

The prospects for future helicopter use in delivering retardants has been slow to take hold in the Rocky Mountain West. Although this runs counter to the trend in other parts of the country, delivery of water, rather than retardant, continues to be viewed as their primary assignment. However, until improved copters become available, they can best be used for transporting men, equipment, and supplies, or for patrolling, rather than for hauling either water or retardant. Hopefully, this situation will change when Vietnam hostilities cease and more versatile ships become available.

Operating costs appear to be the main deterrent to helicopter use, but the logistics of retardant mixing, handling, and storage are also deterrents. Also, drop speed is sometimes too slow for good dispersion, and loading with water is much easier than loading with retardant. Larger capacities and more efficient dispensing devices (including easy hook-on and release), more and better helipads, and portable slurry stations are needed.

In areas of low rainfall, pits are sometimes dug to store water for livestock, wildlife and game birds. One subunit would like to eventually install enough such "trick tanks" so that none would be more than 5 minutes flying time away from another. These "trick tanks" normally hold 70 to 80 gallons; thus one helicopter load would quickly deplete a tank. However, this amount of water in a strategic location could be crucial, so the tank would have to be refilled as soon as possible.

SERVICE FACILITIES

The availability of reliable contractors varies. There is a considerable turnover in personnel, as well as in contractors, in some areas. However, some subunits report that they are able to obtain competent pilots under contract for initial attack. Contractors that follow the fire seasons from south to north, and back again, are needed. This would enable them to develop a more stable and experienced flying organization.

Airfield standards also vary. In some areas the cities or counties have made improvements, while in others the user agencies have had to make the necessary renovations. Wind, terrain, and location sometimes pose hazards. Some retardant bases have had to relocate in order to accommodate other air traffic.

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Generally, the location of retardant bases indicates that considerable foresight and sound planning have gone into site determination. However, some have shortcomings; for example, the number of available aircraft. If the base is a long distance from the fire, more than one plane may be needed to supply a sufficient flow of retardant. Also, the wide scattering of areas in which fires can occur might result in excessive flight time. Establishment of satellite bases having aircraft on temporary standby could cut down excessive flight times considerably.

The possibilities of a unified, intra- and interagency approach toward areas having common protection problems should be thoroughly explored. Similarly, there are opportunities for making maximum use of the nearest retardant base. The strategic location of interagency bases in most cases could reduce flight time and might encourage more use of slurry at the time it would be most effective. Therefore, the optimal location of bases in respect to predicted fire incidence and flight time also needs more analysis.

Communications between ground crews and aircraft are not always good. There is a special need for direct communications during initial attack between the air tanker pilot and the fire boss. Also needed are interagency radionets and closer supervision over the types and wording of messages.

DELIVERY BY GROUND TANKERS

Retardant delivery by ground tankers is now in about the same phase as the early stages of delivery by fixed-wing aircraft approximately 10 years ago. But results to date have been rather disappointing because of problems with mixing, handling of bulky materials, corrosion, and application. Use of ground tankers in the future for pretreatment of prescribed burned areas offers some possibilities. Development of the use of ground tankers on wildfires may lag behind such use.

To facilitate retardant delivery by ground tankers, a chemical mix is needed that (a) is instantly soluble, (b) will stay in solution indefinitely, (c) is nonirritating, (d) maintains its color, (e) is noncorrosive, and (f) is not bulky. However, these improvements wouldn't help much in areas where little water is available. Specifications and instructions for ground tanker use are critically needed, as well as a retardant that is developed specifically for use on range fires.

One user reported that application of retardant by ground devices is at least three times more efficient than application by air, provided that the fire perimeter or a tenable control line is accessible to the tanker. A common pattern of ground use is to have 200- to 400-gallon tankers plus a 500-gallon "mother" tanker.

RETARDANT USE FOR PRESCRIBED BURNING AND PRESUPPRESSION

Nearly two-thirds of the retardant users contacted personally do not use retardants in prescribed burning. Even among those who did, such use is restricted by the characteristics of the chemical formulations that are now available. It appears that ground tankers will be preferred for any future use in prescribed burning, but application by air tankers should not be ruled out. Several projects for developing more suitable ground units are underway.

Similarly, nearly three-fourths of the retardant users reported that they did not use retardants in presuppression along roads; furthermore, they did not indicate that they would use a "rainproof" type of retardant if it was developed. In the fireproofing of roads, the use of ground tankers would offer distinct advantages over air tankers.

Cost-Benefit Considerations

Just what is the role of retardants in fire management? Aerial delivery of retardants, along with other improved air operations, have completely revolutionized fire control methods within recent years. These operations have been most effective in areas having highly flammable fuels, extreme weather conditions, rugged terrain, high resource and improvement values, and dense populations. The role of retardants is less pronounced in prescribed burning and presuppression measures.

Inasmuch as the use of retardants is seldom a solitary event, the determination of benefits that can be attributed solely to the application of retardants is often difficult. It might be true that the containment of just one, small, potentially disastrous fire more than offsets the entire cost of the retardant program at a base for an entire year or for several years. The Caribou Fire that was contained and the Sundance Fire that wasn't, both of which occurred in northern Idaho in 1967, can be cited as proof of this contention. More pragmatically, the relative cost per chain of held line "constructed" by retardants as compared with other line construction methods might be more pertinent.

Nevertheless, there is a recurring need to examine the cost-benefit relationship between fire suppression costs and the value of resources protected (67). Such an examination should include consideration of alternative defensive measures (73). Of the two major elements, ("cost" and "benefit"), cost is usually the easier to determine or estimate. For example, one unit that experienced approximately the same burned acreage and number of class E fires in 1961 as it did in 1967, estimated that the average suppression cost per acre was $67 in 1967 as compared to $125 in 1961. This reduction was attributed to (a) the use of retardant on initial attack, (b) use of organized fire crews, (c) minimum suppression action on high country fires of low resource value, and (d) better business management practices by fireline personnel (96). Reliable damage cost estimates were not available.

Traditionally, major emphasis has been directed toward appraising the damage to the timber resource (60, 61); in recent years, the estimation of damage to other resource values has received increased attention. However, Flora (37) explains that "six decades and more of study have not provided guides to tell, across the range of conditions facing most forest managers, how much of any of these damages will result per acre burned." It would seem that irreparable soil damage, or soil loss or creep, should be the standard for appraising resource damage. However, resource damage does not tell the whole story, because economic and social factors must be considered too (1).

Perhaps precise cost-benefit relationships are not even needed to justify retardant programs. This has already been recognized by others.

> There. . . (are many). . . cases in which benefits from competing programs are roughly equal, and where sensible choices can be made on the basis of costs alone. Similarly, if one program generates larger benefits than others, a basis for rational choice exists if costs of the superior project are as low or lower than those of competing alternatives even though benefits cannot be measured precisely (16).

The primary advantage to date of aerial delivery of retardants has been their speedy application to contain small fires until ground crews can arrive to extinguish them. This objective ties in very well with the "10 a.m. policy" that was inaugurated by the USDA Forest Service in 1935; this policy pointed up the following: (a) The need for a definite unequivocal action policy; (b) recognition of the fact that aggressive initial action is the cheapest in the long run; (c) frank recognition of the fact that damageable forest values are changeable and difficult to determine; and (d) the need to build and maintain morale in fire suppression (28). In 1941, however, Gisborne (44) raised some questions concerning this policy. He stated that:

> If and when that policy becomes clearly recognized as a temporary expedient, I believe that it will rate a milepost. If, however, it has already become or ever does become the death knell of all previous objectives based on damage, then it rates a tombstone executed in the blackest of black granite. . . .if the main idea of the policy was to control fires while really small, the use of a time criterion would seem to be open to further investigation; for fires can be caught small and cheaply, often more cheaply, without controlling them by 10 a.m. tomorrow.

Gisborne's concept is gradually winning acceptance as evidenced by the policy of "minimum suppression action on high country fires of low resource value." This was one of the reasons cited by the unit that reduced suppression cost from $125 to $67 per acre between 1961 and 1967. This unit's interpretation of the "10 a.m. policy" poses an expanded role for retardant use because of its holding and deliverability capabilities. Thus, the continuing importance of this vital aid to fire control and management is assured.

Conclusions

In spite of the rapid rate of change in retardant use, those associated with the program have displayed remarkable versatility in adjusting to ever-new materials, procedures, and techniques. And although the cost has been large, little doubt remains that retardant programs have paid their way through reduced resource damage.

Now, however, rising land and resource values, and increasing cost-consciousness have raised the question of whether retardants could be applied even more efficiently than they have been in the past. By anticipating future needs and capabilities, rather than keeping pace with current improvements, it should be possible to provide better direction for retardant programs and planning.

An analysis of the discussions with the interviewees, and of the conference recommendations, resulted in several conclusions that should be of concern to fire managers and fire control specialists.

1. The use of chemical retardants poses a threat of injury to retardant users, and their effects when combined with chemical use in other land management activities might result in unacceptable pollution in some areas. Therefore, administrators of agencies that use retardants should establish and distribute guidelines for the safe handling, application and disposal of fire retardant materials. Functional inspections should consider health, safety, and pollution aspects.

2. A combined program of well-thought-out, thoroughly synchronized research and administrative studies and equipment development tests is needed to coordinate in the quickest time practicable the most essential knowledge regarding fire retardants. This would enable a simultaneous attack on the most pressing problems confronting retardant users.

3. Information on fire retardants at all levels and for all agencies is inadequate. There is too long a timelag in getting acceptable formulations and products into agency directives. These shortcomings could be alleviated by (a) developing a method for compiling and disseminating statistics on the total use and cost of retardants, (b) providing for more rapid, widespread dissemination of experience information on new fire-retarding chemicals, and (c) notifying field units immediately when a new retardant is accepted for operational use. In addition, it would be helpful to develop simplified terminology and better guidelines on all phases of retardant use for field distribution.

4. It sometimes appeared that insufficient detail in declared policy provided an inadequate basis for making sound, consistent decisions on retardant use. The situation could be improved by reviewing policy at the various administrative levels to definitely determine whether firm written policy or general guidelines provide the best direction. Once a particular course of action is decided on at the higher levels, it would be beneficial to explain the policy and the reasons for it to lower-level decisionmakers.

Consistent interpretation of policy by decisionmakers could also be aided by the development of uniform policy between and within agencies where practicable. More precise definitions of when retardant drops should no longer be used are particularly needed.

5. The ever-increasing obsolescence of the World War II vintage aircraft, which deliver most of the retardants dropped on fires, becomes more critical with each passing year. In 1967, for example, it was expected that the tanker fleet would be drastically reduced by 1973 if the rate of attrition at that time continued without adequate replacements. Thus decisions should be made very soon on the kinds of fixed-wing aircraft needed to replace the older models. Newer models of the V/STOL (vertical, short takeoff and landing) type appear to hold considerable promise for future retardant deliveries. Equipment development specialists should be in a good position to advise air operations administrators on replacement needs and capabilities.

In situations where retardants are dropped before ground firefighters have reached the scene, heavy dependence is placed on the ability of initial attack pilots (and other airmen) to select the correct targets. Training in fighting wildfires on the ground, or at least, closehand observation of wildfires from the ground would improve their capabilities. However, the

optimal role of lead planes and their accompanying observers appears somewhat ambiguous. Studies by air operations administrators and fire management scientists could help clarify this apparently vital role.

6. Helicopter operating cost appears to be the main deterrent to their increased use for delivering retardants. Other important considerations are retardant mixing, handling, and storage, and quick turnaround time. Larger capacities and more efficient dispensing devices (including easy hook-on and release), more and better helipads, and portable slurry stations are also needed.

Improved logistics of retardant use by helicopter and a continuing program for reassessing helicopter capabilities for delivering retardants would facilitate the optimal use of this versatile machine. A joint reassessment by equipment development specialists and air operations administrators could aid in this endeavor.

7. The survey revealed considerable differences of opinion on how fire-retarding chemicals should best be applied. These differences were compounded by the natural variations in vegetative cover type, terrain, and weather conditions. A comprehensive survey of retardant users to definitely determine what is desired in retardant dispersal would be helpful in establishing retardant application goals and objectives.

Several studies, surveys, and analyses have been made with varying results in attempting to estimate the efficiency of retardant drops on wildfires. There is a continuing need for this kind of assessment in order to help place the cost-benefit relationships of retardant programs in their proper perspective. Many of the estimates may have been unreliable because measurement of accomplishment was unwieldy. Perhaps the procedure could be simplified, without loss of accuracy, by distinguishing between those fires positively held to small size (10 acres or less) and those that could have been held to small size if enough retardant had been applied in the right place at the right time. Dependable experimental design for estimating the efficiency of retardant drops could be developed by qualified mensurationists.

8. Better use of chemical retardants could be achieved through the improvement of operational procedures. Some of the areas that would benefit from scrutiny by air management officers and fire management scientists are:

a. Automatic dispatch of retardants;

b. Intra- and interagency dispatch of retardants;

c. Optimal number and size (capacity) of retardant aircraft needed at existing retardant bases;

d. When to dispatch large planes (with retardants) and when to send small planes;

e. Optimal location of retardant bases, regardless of land ownership;

f. Best mix of aerial and ground retardant delivery, helitack and ground crews, and smokejumpers at particular bases; and

g. Scheduling of contractor retardant-delivery aircraft according to fire season variability from area to area.

9. Quality control of all phases of operation at retardant bases is imperative if results of research and equipment development efforts are to be of value. Air tanker base contracts should be extended for the second and third years to improve continuity of operations.

Retardant mixing practices could be improved by (a) evaluating the potential for portable retardant mixing plants, (b) determining methods for achieving better retardant mixing crew stability, and (c) determining the relative advantages and disadvantages of user mixing of retardants versus contractor mixing. In addition, the impeller performance on the USDA Forest Service (Lely) and California Division of Forestry mixers should be matched to simplify formulation problems for suppliers. Retardant bases should be designed and maintained for flexibility to handle any acceptable (qualified) formulation.

Equipment development specialists and air management officers could collaborate in matching the two mixers and designing retardant bases. Future all-purpose equipment will require certain compromises and might be less efficient and more costly.

Joint study could also help solve a number of problems in the handling and storage of retardants. For example, it would be well to determine whether it is feasible or desirable to store slurries of more than one chemical, salt content, and/or viscosity at a particular retardant base. In addition, the bulk handling silo system should be (a) compatible with any similar dry retardant chemical, (b) owned by the responsible fire agency to promote competition among chemical suppliers, and (c) capable of being filled by either pressurized bulk trucks, unpressurized bulk trucks, or manually broken bags. A positive means of agitating the bulk material or of adding to the formulation is necessary to break loose packed material and to avoid "bridging."

10. Long-term chemical formulations prepared for ground tanker use might be more appropriate for helitanker use than are the conventional aerial retardants. The possible need and requirements for a helitanker formulation should therefore be determined with the assistance of research and equipment development chemists as well as the possibility of using ground tanker formulations for helitankers. It seems reasonable to require acceptable corrosion rates for all retardant formulations on aluminum, brass, and steel parts in retardant systems.

The liquid concentrate form of fertilizer salts has been used operationally as a fire retardant within the past few years. It has served as a versatile and effective material. Fire control and equipment development specialists should keep abreast of system improvements for handling it and be ready to extend its use when and if the time comes.

An extender is a chemical added to a retardant formulation to make it more resistant to weathering. To date no extender has been proven to be of sufficient value to be adopted for widespread use. However, potential use of a successful, persistent (waterproof) fire retardant is great. An analysis of the incidence of roadside fire starts would pinpoint areas where it should be applied once it is developed.

Interest in wetting agents has evidently become a bit lopsided. Field use does not appear to be increasing, but many manufacturers are wanting their product used. Inasmuch as there now are many qualified products, new materials need not be solicited. Future testing should be limited to carefully screened products. Agency administrators could keep their field personnel informed of the current situation by listing wetting agents meeting minimum requirements in an annual amendment to their respective directives system.

Suggested Areas for Study

Coordination between administration, equipment development, and research units is needed to solve other aspects of retardant use, because no one unit can progress without the assistance of the other two. Although fire managers and fire control specialists should be concerned with these other areas of use, investigation of many of them could more profitably be centered in research or equipment development projects.

Coordination would enable the forest fire research laboratories to study burning under many independent variables. Such could include simulators to extend laboratory findings and an array of well-designed field applications. This could culminate in an intensive study of what really happens when retardants are applied on actual fires.

Some examples of specific problem areas that would benefit from a coordination of efforts are (a) rheological properties, (b) pilot plant simulation, (c) determination of how to penetrate a dense canopy with retardants in order to stop a fast-moving ground fire on a wide front, and (d) determination of the different kinds of retardant swaths that are most effective under various fire conditions.

The following are more general problem areas that are suggested for study.

HEALTH, SAFETY, AND POLLUTION ASPECTS

Public health and safety hazards could be minimized by making needed improvements in (a) base locations, (b) mixing plants and other basic equipment, (c) storage facilities to prevent tank rupture and overflow, and (d) mixing procedures including the disposal of waste liquids. New formulations submitted for approval should be subject to bioassay and toxicity tests.

Investigation of the combined effects of retardants and other chemicals used in land management activities might help forestall potential pollution problems. Comparisons of the relative ultimate damage potential to the environment between using retardants and letting an area burn would also be helpful.

Reports of damage to livestock appear periodically. Controlled tests by research chemists would provide a better basis for estimating the extent, if any, of damaging effects of retardant chemicals on livestock.

DISSEMINATION OF INFORMATION

Formal written information on retardants reaches a large number of users, but is less efficient than personal contacts, films, showmobiles, and simple "how-to" instructions. Demonstrations and group instruction, such as the 1964 retardant seminars, are probably the most

effective methods of keeping retardant users informed of new chemical formulations and mixing and delivery procedures. A continuing, combined effort by research chemists, equipment development I and E specialists, and air management officers is needed to make current information available for field use.

FIXED-WING AIRCRAFT

Critical replacement needs and desired capabilities for future fixed-wing aircraft should be determined by equipment development engineers and air operations administrators. Similarly, a research approach might benefit air management officers in their assessment of the optimal role of lead planes.

DISPENSING METHODS

Air tanker gates have not been improved significantly in recent years, but application rates need further study first. Once rates and viscosity ranges are established, the delivery system can be improved. Some have suggested getting the door out of the way faster. Both a mathematical and a simulated approach to the aerodynamic problems might be needed. The direction for helitankers has been toward detachable tanks and buckets that can be sized and attached to most makes and models of helicopters, but it appears that performance is sacrificed in this approach.

Studies should be undertaken to determine whether it would be feasible or desirable to design a plane around an optimal dispensing device. Also, improved airtanker and helitanker gating systems should be engineered or other improved dispensing devices should be developed by equipment development engineers.

HELICOPTERS

The great diversity of helicopter models and size classes makes their use expensive. Few fire control agencies own their own helicopters; this, coupled with the trend toward manufacturing larger helicopters, makes the cost problem more complex. Furthermore, some form of mechanical ejection device might be needed if larger rotocraft are used.

Equipment development chemists and engineers might undertake additional studies to determine whether or not retardants contaminate helicopters. They might also investigate the feasibility of using modified Mead helitanks to dispense retardants.

GROUND TANKERS

Though use is limited in some areas, much interest exists in delivery by ground tankers. Past results, however, have been rather disappointing. Furthermore, problems with mixing and handling of bulky materials, corrosion, and application have been encountered. The possibilities for expanded use of ground tankers should be determined by equipment development engineers.

FIELD TESTING

The performance of chemical formulations in retarding a fire can be precisely measured under carefully controlled laboratory conditions. Performance on a wildfire, however, is much more difficult to gage. Field testing is needed to more nearly relate laboratory expectations to accomplishments on wildfires. Research in the following four areas might produce fruitful results: (a) Whether or not diammonium phosphate does enhance wood combustion; (b) the amount

of retardant actually required per unit of fuel or acre; (c) detailed aerial application rates by major fuel types found throughout the United States; and (d) methods for measuring salt concentrations according to various dispersal patterns.

An efficient method also needs to be developed for field testing new retardants and for widespread dissemination of results. This should include the following: (a) Determination of fire-retardant properties and comparative effectiveness of the various salts; (b) specific recommendations on the best products to use under various fuel, fire intensity, terrain, and weather conditions; and (c) distribution to the field of a clear, complete, and concise listing of the properties of retardants that are approved for use.

The latter activities should be a joint undertaking of research and equipment development chemists with fire control officers assuming responsibility for distribution of results.

IMPROVEMENT OF AIR OPERATIONS

Studies by fire management scientists could result in improved air operations. Such studies might include: (a) determination of the advantages and disadvantages of early morning drops of retardant; (b) inclusion of the optimal use of retardants in preattack planning; (c) redefinition of initial attack and followup as they pertain to retardant use; and (d) development of training procedures for users in how to distinguish between strategic and tactical objectives.

RETARDANT BASES

Tighter standards for contract base operations need to be established by equipment development engineers. Closer control also is needed to maintain established standards of operations, quality control, and good safety practices because original equipment is deteriorating and new or replacement equipment must be selected.

If mixing is done by a contractor, it is imperative that measurement standards for viscosity and salt content be included in the contract and that these measurements be checked frequently by the contracting agency. Research chemists should continue to develop standards for such measurements as well as for frequency of testing.

Equipment development engineers should determine the need for operations research or for the use of a systems engineering approach in developing suitable base systems, including demand mixing and bulk storage. They should also determine the costs for a new type of base that would be equipped with a Silo-Monsanto Ejector-Mixer-Holding Tank and Distribution System using Phos-Chek X-A retardant.

LONG-TERM RETARDANTS

Although the diammonium phosphate and ammonium sulfate chemical formulations (Phos-Chek and Fire-Trol) have proved to be generally satisfactory, interest in liquid concentrate retardants is increasing. Research chemists should study the chemical aspects of various types, concentrations, and thickening agents for liquid concentrates in respect to overall effectiveness. A joint effort by research and equipment development chemists should determine the effectiveness and/or limitations of unthickened liquid phosphate systems on test fires or wildland fires in the Western United States, and the optimal method to be used in preparing, handling, storing, and applying liquid concentrate retardants.

Research chemists should place emphasis on the development and evaluation of retardant formulations containing extenders. They also should (a) undertake a study to determine the feasibility and desirability of developing chemical fire suppressants; and (b) investigate the possibilities of using retardant carriers other than water, such as dusts, gases, and other media.

SHORT-TERM RETARDANTS

Use of short-term retardants within the United States is almost nonexistent for fixed-wing aerial delivery and has not maintained its popularity for helicopter and ground use. Reasons for this reduction in use center mainly around inconvenience, mixing complications, and the question in the operator's mind as to whether thickened water is actually much better than plain water. Future studies on short-term retardants, wetting agents, and foams should be confined to ground and helicopter use where logistics or fire situations prohibit use of long-term products or other nonretardant-oriented control measures.

Accordingly, work should be curtailed on short-term retardants, but research chemists should monitor the market to keep abreast of new developments. They should limit their testing to only carefully screened products. Research chemists should also investigate the penetration of moisture and salt from wetting agents into such materials as peat, muskeg, and tundra, and should verify the toxicity of such agents. (Equipment development chemists are already verifying the corrosiveness of wetting agents.)

SPECIFICATIONS

The General Services Administration, which is responsible for purchasing for federal agencies, had been using a "brand name or equal" purchase description, but is reluctant to continue this practice. The various State agencies also had been experiencing procurement problems. In 1969, research and equipment development chemists and fire control officers prepared a performance specification for long-term, dry type, airtanker retardants. Similar joint efforts are also underway for preparing specifications for other types of retardants when the volume of use increases to a significant level.

There is a continuing need for retardant research specialists to (a) establish a set of standards for each type of formulation, (b) determine the feasibility of developing chemical specifications for improved retardants, and (c) modernize and publish standards and evaluation procedures.

COST-BENEFIT RELATIONSHIPS

Determination of the relation between the costs and benefits of retardant programs is a difficult, complex problem. Costs are high, but so are the presumed benefits. There also are many intangibles, particularly when retardant use is considered in the light of other fire suppression and management tools and methods.

Paradoxically, sound estimates are needed of cost and benefit inputs to develop meaningful equations, but unless the costs incurred and the benefits gained approach a true balance, the inputs could be misleading. Nevertheless, a useful area of study by fire management scientists would be the development of simplified cost-benefit relationships for determining the break-even point of retardant use because even though retardant programs are expensive, resource values are continuing to increase.

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USDA Forest Service
Research Paper INT-104
1971

PONDEROSA PINE PLANTING TECHNIQUES, SURVIVAL, AND HEIGHT GROWTH IN THE IDAHO BATHOLITH

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ACKNOWLEDGMENT

Many people have contributed to this study during the 8 years of its duration. James D. Curtis prepared the study plans, installed the studies, and made the first analyses. Marvin W. Foiles worked closely with Curtis until Curtis retired in 1966. Foiles transferred in mid-1967. Dale Potter and Gary G. Baertsch, Forestry Technicians, successively assisted with the field installations and measurements. Krassel District Ranger Howbert W. Bonnett and his successor Edwin A. Heikkenen coordinated the logging operations at Zena Creek with plot treatment needs. Project Sales Officer Larry Finn helped locate suitable plot areas and supervised the planting crews.

USDA Forest Service
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August 1971

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PESTICIDE PRECAUTIONARY STATEMENT

Pesticides used improperly can be injurious to man, animals, and plants. Follow the directions and heed all precautions on the labels.

Store pesticides in original containers--out of reach of children and pets--and away from foodstuff.

Apply pesticides selectively and carefully. Do not apply a pesticide when there is danger of drift to other areas. Avoid prolonged inhalation of a pesticide spray or dust. When applying a pesticide it is advisable that you be fully clothed.

After handling a pesticide, do not eat, drink, or smoke until you have washed. In case a pesticide is swallowed or gets in the eyes, follow the first-aid treatment given on the label, and get prompt medical attention. If the pesticide is spilled on your skin or clothing, remove clothing immediately and wash skin thoroughly.

Dispose of empty pesticide containers by wrapping them in several layers of newspaper and placing them in your trash can.

It is difficult to remove all traces of a herbicide (weed killer) from equipment. Therefore, to prevent injury to desirable plants do not use the same equipment for insecticides and fungicides that you use for a herbicide.

NOTE: Registrations of pesticides are under constant review by the U. S. Department of Agriculture. Use only pesticides that bear the USDA registration number and carry directions for home and garden use.

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ABSTRACT

Site preparation and mulching tests were carried out on some steep slopes having shallow soils in the Douglas-fir—Ninebark habitat type on the Boise and Payette National Forests. Treatments included: (1) hand scalping; (2) a herbicide; (3) spot burning; (4) periodic hand weeding; (5) straw mulch; (6) black plastic film mulch; and (7) glass fiber mulch. Other natural variables recognized were: (a) aspects; (b) soil depth; (c) moisture relations; (d) summer rainfall; (e) temperatures above undisturbed vegetation and above surfaces of treatments (4), (6) and (7). Survival and 5-year height growth of the outplanted 2-0 nursery stock were measured. Extensive mammal damage was noted and appeared to be indirectly correlated with soil depth. All treatments increased seedling survival. Observations suggest that combining hand scalping and herbicide is most promising in terms of cost and effectiveness. Height growth was positively correlated with plot survival percent and soil depth. Trees were tallest where black plastic film was used and on SE aspects; such growth was probably related to the influence of warmer temperatures.

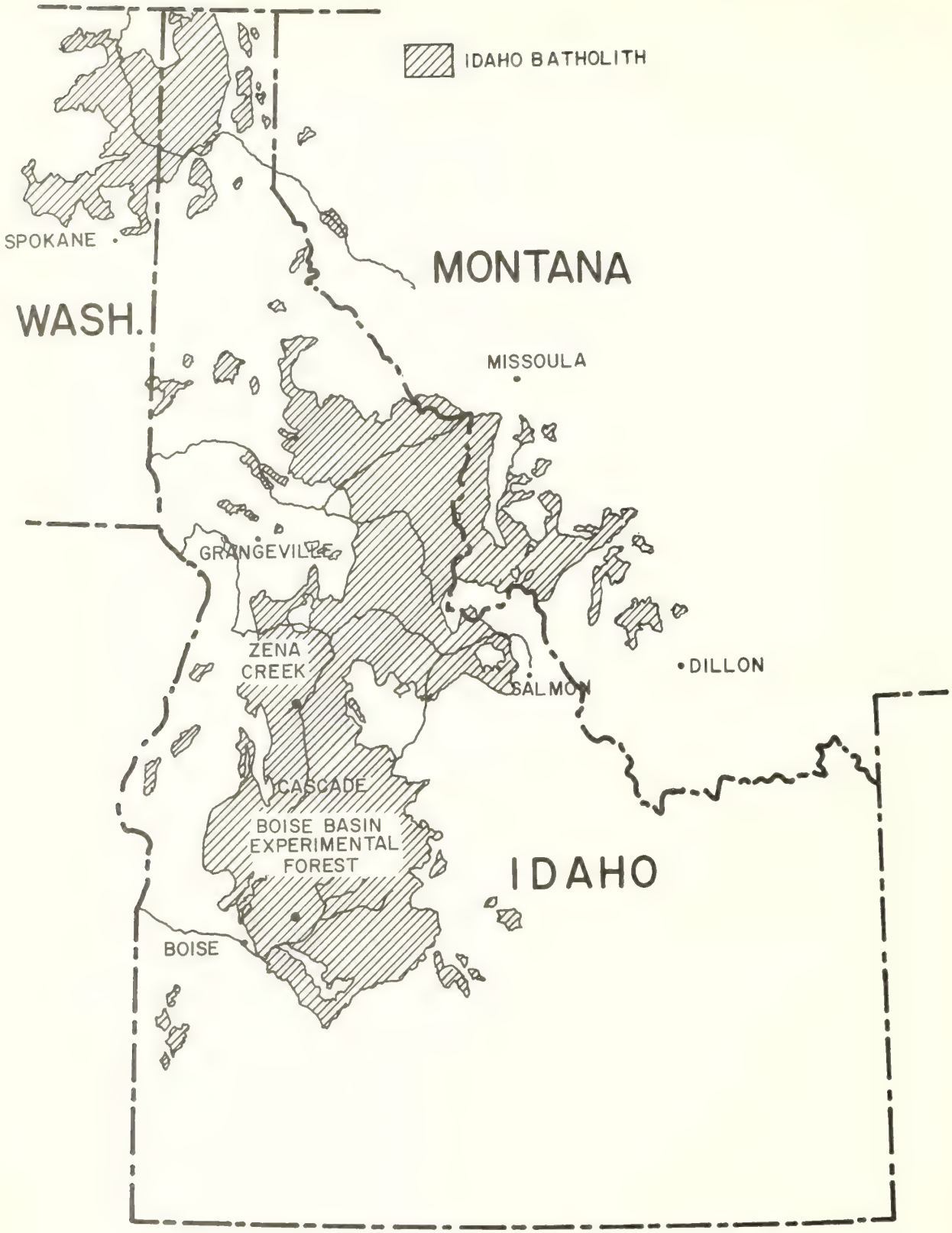

Figure 1.--Map of the Idaho Batholith. (From USGS Map.)

Introduction

The Idaho Batholith (fig. 1) has some prominent characteristics which are serious obstacles to forest management and regeneration. The shallow, granitic soils are notably coarse grained and provide severely limited moisture storage and a high evaporative potential.[1] [2] On steep slopes these soils have a high inherent erosion potential (Megahan and Kidd).[3] High intensity rains (Kidd 1961; 1964) from frequent and unpredictable summer convectional storms further aggravate erosion potentials. These storms also provide some relief from soil moisture deficits. Established vegetation makes almost full use of available soil moisture but stabilizes soil in the process.

The land manager faces a dilemma. If trees are to be harvested, he must find ways to maintain a vegetative cover to control erosion yet reduce vegetative competition so that replacement seedlings have enough soil moisture to survive and grow. Furthermore, his harvesting methods will be severely limited by the steep slopes.

A series of ponderosa pine (*Pinus ponderosa* Laws) planting tests in the Idaho Batholith (1961 to 1964) were primarily concerned with controlling vegetative competition at the time the seedlings were planted and for several years thereafter.[4]

We evaluated hand scalping, a pre-emergence herbicide (simazine),[5] spot burning, and periodic weeding techniques, mulches of straw, plastic film, and glass fiber (table 1). Slope aspects and soil depths were other variables considered. Highly variable climatic factors occurring from year to year were a confounding influence.

Four tests were installed on the Zena Creek logging study area, Payette National Forest, and one test at the Boise Basin Experimental Forest on the Boise National Forest (fig. 1).

Tests were installed in habitat types (h.ts.) that closely resemble, and probably are, the Daubenmires' (1968) *Pseudotsuga menziesii - Physocarpus malvaceus* (The Douglas-fir--Ninebark h.t.). Our results specifically apply to this presumed h.t. and should only be extended to other h.ts. with reservations. The seral nature of ponderosa pine occurrence in this h.t. is important in any consideration of regeneration.

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[1]Richard Alvis, John Arnold, and others. Soils of the Zena Creek Logging Study, Payette National Forest. 1960. (Unpublished report on file (2510) at USDA Forest Serv., Region 4, Ogden, Utah.)

[2]O. C. Olson. A soil survey report of the Boise Basin Experimental Forest. 1965. (Unpublished report on file (2510) at USDA Forest Serv., Region 4, Ogden, Utah.)

[3]Walter F. Megahan and W. J. Kidd, Jr. Effects of logging and logging roads on erosion and sediment deposition from steep terrain. In preparation. USDA Forest Serv., Intermountain Forest and Range Exp. Sta., Ogden, Utah.

[4]Dale O. Hall. Conifer planting techniques, survival and height growth in the central Idaho batholith. 1969. (Unpublished final report for Study FS-INT-1202-494 on file at USDA Forest Serv., Intermountain Forest & Range Exp. Sta., Ogden, Utah.)

[5]Simazine is the common name for 2-chloro-4, 6-bisethylamino-1, 3,5-triazine.

Table 1.--*Planting test constants and variables*[1]

Test number	Year	Aspect	Average soil depths	Treatments: Site preparation	Treatments: Mulch
			Inches		
			ZENA CREEK LOGGING STUDY AREA		
I	1962	SW	17 -24	Scalps Pits Furrows	Straw None
II	1962	SE to W	--	2' scalp 4' scalp 6' scalp Burned spot	None
III	1963	East (SSE to E) West (SW to NNW)	16 -31	Pits	Glass fiber Black polyethylene None
IV	1964	ESE	24 -31 +	Pits	Glass fiber Black polyethylene Simazine None
			BOISE BASIN EXPERIMENTAL FOREST		
V	1964	SSW	20 +	Scalps	Glass fiber Black polyethylene Weeded None

[1]A single column item listed for a test number represents a constant, multiple items, the test variables.

Some of the wildlife species that browsed and foraged on test seedlings have been tentatively identified as:

Rocky Mountain mule deer--*Odocoileus hemionus hemionus*

Rocky Mountain elk--*Cervus canadensis nelsoni*

Snowshoe hare--*Lepus americanus*

Northern pocket gopher--*Thomomys talpoides*

Porcupine--*Erithizon dorsatum*

Harvesting limitations dictated patch cuts of one to several acres. Logging generally took place the year before the study areas were planted. All planting was done by hand with a shovel using 2-0 nursery stock from the Lucky Peak Forest Service nursery near Boise.

For the sake of brevity, these five tests will be outlined briefly and only the specific results indicated.

Site Preparation, Mulching, and Aspect Tests (Zena Creek)

Test 1: Pits, Furrows, and Scalps, With and Without Straw Mulch, 1962

This first experiment at Zena Creek included tests of three site preparation methods. The three methods were: (a) a shallow hand-dug pit (3 by 3 feet with a horizontal bottom surface for planting); (b) a shallow V-trench or furrow made with a rotocat machine (about 4 feet along the contour); and (c) a scalp (3 by 3 feet). The sites were prepared in the fall of 1961. The 2-0 ponderosa pine seedlings were planted in May 1962. A straw mulch (3 by 3 feet) was placed around half of these seedlings to stabilize soil and conserve moisture; the remaining seedlings were left as planted.

The two test areas were selected to provide a range in soil depths. Both areas were at about a 5,000-foot elevation, on southwest aspects, with slopes averaging 70 percent.

Soil depths were quite variable in each area. Thirty-three soil pits (table 2 and Appendix I) showed a range in depths to bedrock of 7 to 24 inches for Area 1 and 14 to 38 inches for Area 2. Three blocks were established in each area to reduce the influence of this variability on the statistical analysis of survival.

Seedling survival counts on the two test areas were made each fall from 1962 to 1966 (Appendix II). In the analysis of variance of seedling survival, after the 1962 growing season, 48.5 percent of the total variation was due to block differences in areas.

Table 2.--*Average soil depths (inches) to bedrock, Test 1 (Zena Creek)*

Site preparation	Test area 1	Test area 2	areas
	STRAW MULCH		
	Inches		
Scalps	13.7	25.3	19.5
Pits	11.0	22.3	16.7
Furrows	16.0	25.7	21.8
	NO MULCH		
	Inches		
Scalps	19.3	29.3	24.3
Pits	18.8	25.2	22.0
Furrows	20.0	19.7	19.9

The mulch/area interaction was highly significant (p = .01) in 1962 (fig. 2). Although seedling survival on Area 2 was higher under a straw mulch than under no mulch, the situation was reversed on Area 1. A tentative inference is that mulching on the deeper soils helps conserve enough moisture to improve survival. It doesn't help on shallower soils because the reservoir of moisture just isn't large enough to meet normal evapotranspiration demands and new seedling demands too. By 1966 this mulch/area interaction had decreased but was still significant (p = .05).

A highly significant mulch/site-preparation/area (3-way) interaction was present in 1962 (fig. 2). By 1966 this 3-way interaction had lost all significance.

The extent of terminal damage over the $6\frac{1}{2}$ years became evident when the seedling heights were measured in October 1968, seven growing seasons after planting (Appendix III). On Test Area 2, 82 percent of the seedlings alive at the time of height measurements showed terminal damage; on Test Area 1, 58 percent showed terminal damage. The damage to most stems was of the type ascribed to hares (Lawrence, Kverno, and Hartwell 1961). Deer and elk were probably the next most important causes of damage. Such depredations were probably responsible for some seedling mortality as well. There did appear to be a correlation of soil depth with percent of seedling damage (fig. 3). Seedlings on deeper soils, growing more vigorously, may have had tissue that was more succulent, or less resinous, or perhaps they were associated with a greater quantity of edible plants tending to concentrate animals and giving an increased probability for browse damage.

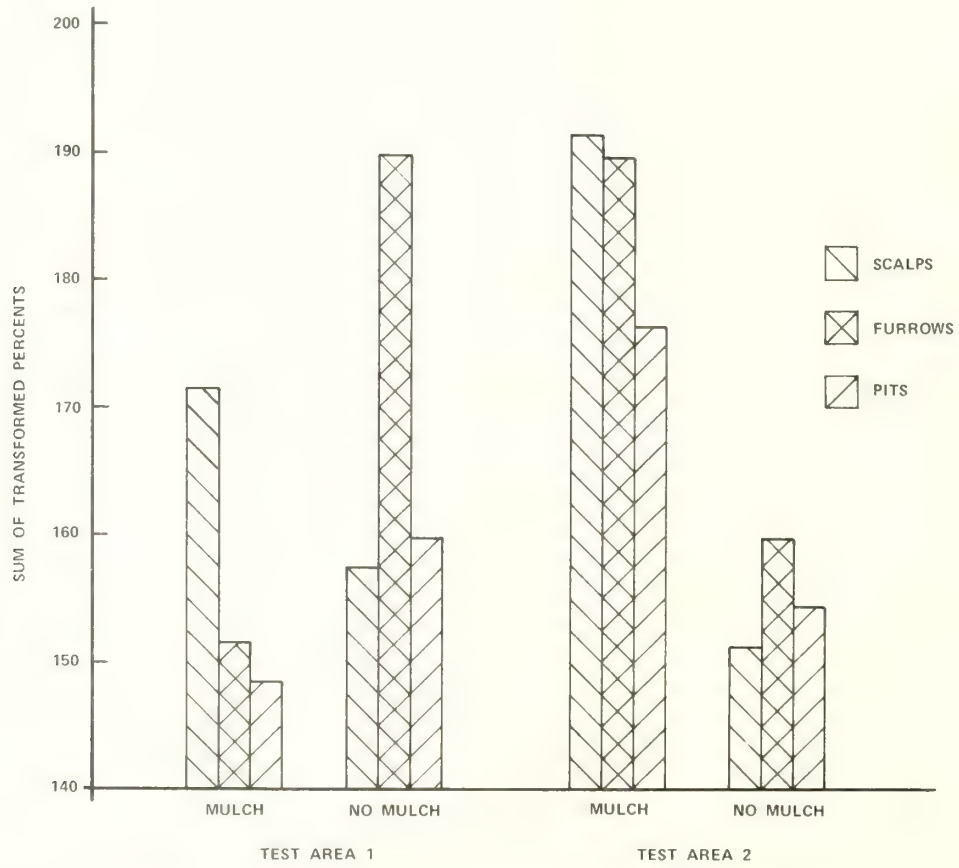

Figure 2.--Interactions between mulches, site preparation, and areas, 1962.

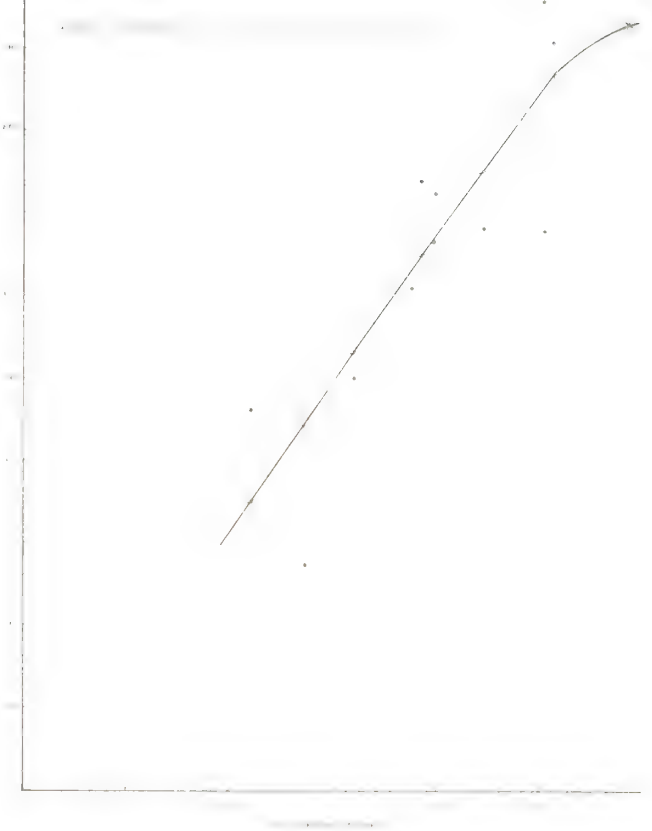

Figure 3.--Soil depth and seedling damage percent (1968) by areas and treatments.

Treatment differences were not apparent in seedling heights. The average heights for 1966 and 1968, for seedlings alive in 1968, were:

	Soil depth (Area)	
	8-16	20-40
	Normal seedling height (Feet)	
1966	0.83	1.01
1968	1.24	1.72
	Damaged seedling height (Feet)	
1966	0.77	0.94
1968	1.10	1.44

Average annual height growth (1966 to 1968) for normal seedlings on the shallow soil was 0.20 foot per year; on the deeper soil (Area 2), it was 0.30 foot per year.

Test 2: Burned Spots and 2-, 4- and 6-Foot Scalps on Two Aspects, 1962

In 1961 some ponderosa pine seedlings had been planted on burned-out slash piles. Random field observations suggested that better survival and growth occurred on these burns. Thus, it was assumed that an alternative, a scalped planting site, would hold promise for a similar reduction in competition.

In this test, survival levels were compared on three sizes of scalps (2, 4, and 6 feet in diameter) and on burned spots. Three areas were selected, all on the same soil type. Two areas had westerly aspects (A and B), the third faced easterly. All vegetation and the top 4 inches of mineral soil were removed by scalping. On the other hand, the direct effects of spot burning probably did not exceed 1 inch in depth. There were 287 ponderosa pine 2-0 seedlings planted in May 1962, of which 40 were on the east aspect. Survival counts were made each fall for 5 years (Appendix II). The percent of survival in the fifth year was as follows:

Treatment	*Aspect*		
	East	*West "A"*	*West "B"*
	- - - - - - - *Percent* - - - - - - -		
Scalps:			
2-foot	27.3	42.6	36.4
4-foot	60.0	46.3	72.7
6-foot	33.3	35.4	63.6
Burned spots	55.6	55.8	69.2

A chi-square test of the independence of the four treatments (testing the supposition that survival was not independent of site preparation) was not significant (p = .05). However, a trend in the chi-square value, over the 5-year test period, was apparent:

Year	*Chi-square value*
1962	2.15
1963	2.36
1964	6.76
1965	5.41
1966	7.36

p .05 = 7.81

This trend suggests that if measurements had been continued for 1 or 2 years a significant difference would have resulted. The burned spots and 4-foot scalps maintained the greatest survival percentage after 1964.

The effects from burning were not readily apparent; however, the size of the burned spots which were about 4 feet across may have been as great an influence as the burning treatment itself.

In support of the idea that size of treated area is important, it does appear that a 4-foot scalp gave better survival than either a 2- or a 6-foot scalp. Perhaps the 2-foot scalp (3.1 sq.ft.) was not as effective in preventing or retarding competition as the 4-foot scalp (12.6 sq.ft.) which had four times the cleared surface area. The reasons for the decrease in survival on the 6-foot scalp (28.3 sq.ft.) are not apparent.

Test 3: Pits and Synthetic Mulches on Two Aspects, 1963

The straw mulch used in 1962 seemed to have a slight, beneficial effect on seedling survival. Thus, the use of cheap effective mulches to reduce competition and

increase soil moisture in the vicinity of planted seedlings looked promising. Accordingly, two new mulching materials (black polyethylene film and a light-colored glass fiber blanket) were chosen for testing and comparison with a no-mulch (control) condition.

The two synthetic mulch materials were in sheet form, rolled for shipment. The polyethylene was 4 mils thick, 36 inches wide and 150 feet long and was perforated every 3 feet to facilitate separation. The glass fiber blanket was 1/4 inch thick, 6 feet wide, and 150 feet long and had to be cut into 3- by 3-foot pieces.

East and west aspects were compared. All six plots were located on soils that averaged 20 to 40 inches deep. Sample soil depths, from surface to bedrock, ranged from 12 to 43 inches.

In the fall of 1962, 900 spots 36 inches square were first scalped and then dug out to form a pit of sorts. The pits were allowed to settle during the winter. In early April, 1963, the 150 pits in each of the six plots were planted with a 2-0 ponderosa pine seedling (fig. 4). The three treatments were randomly assigned within groups of three adjacent seedlings. Late in May the two kinds of mulch sheets were spread around designated seedlings and held in place with three to five wire pins (fig. 5). For a total of 50 trees the cost per tree for mulch and installation was: polyethylene-42 cents; glass fiber-66 cents.

Temperatures were measured in early August 1963, at the mulch surface and at the soil surface under the mulch (table 3). The dates and time of day were selected to provide the highest temperature readings for each aspect. Surface temperatures were generally the highest on the black polyethylene; temperatures on the glass fiber surface were consistently the lowest. Soil temperatures beneath mulches were 13 to 18 degrees less than on the mulch surface, and 14 to 24 degrees less than at the exposed soil surface. No heat lesions were found on seedling stems in contact with mulches.

Mulch differences were highly significant in the analysis of variance for survival for 1963 through 1967. Survival was best with a glass fiber mulch (Appendix II). It seems that competition on the "check" plots increased in this 3-year period while with black polyethylene the competition was maintained at a reduced level. Some increased first-year transpirational stresses over the warmer black polyethylene may have caused the initial high mortality. With increasing age and height this factor would have less influence and competition factors would become more important. Fifth-year survival percentages were:

Treatment	*East*	*West*
	(Percent)	
Control (no mulch)	16.1	31.1
Glass fiber mulch	43.3	47.9
Polyethylene mulch	22.0	30.1

The aspects tested (west and east) did not have a significant effect on survival rate. Survival on individual plots during the first year ranged from 98 percent for seedlings mulched with glass fiber on the east aspect to 24 percent on the same aspect with black polyethylene. Furthermore, the interaction between aspect and mulch was not significant.

Although mulch materials did not completely eliminate vegetative competition, they did slow it down, and at many of the installations the effect continued into 1969.

Figure 4.--Soil pit with planted ponderosa pine seedling.

Figure 5.--Glass fiber blanket serves as mulch and is held in place with wire pins.

Table 3.--*Mean maximum recorded temperatures (°F.) at mulch surface and beneath mulch, 8/5/63 and 8/7/63*

Mulch	East (11 to 12 a.m.)		West (2 to 3 p.m.)	
	Mulch surface	Soil beneath mulch	Mulch surface	Soil beneath mulch
	Degrees Fahrenheit			
Glass fiber	141.8	123.7	133.8	115.8
Polyethylene	149.7	131.2	141.6	128.4
None (soil surface)	147.8	--	142.0	--

Animals interfered with the mulch materials, but no mulches were completely removed. Deer, elk, and squirrels were the presumed culprits. In other tests, no mulch/terminal damage relationship was evident. This leads one to believe that there is a low probability for such a bias in this test. I can only guess at the animal/vegetative cover/damage relationship.

Seedling heights were measured in 1967 at the end of five growing seasons after planting. Some of the seedlings had damaged terminals and were excluded from the analysis. Twenty-eight of the 31 damaged seedlings were on one plot which had grass cover but little brush. Other plots had predominantly brush cover. The number of undamaged seedlings and average heights for each treatment, both east and west aspects combined, were:

Treatment	*Seedlings (Number)*	*Height*[6] *(Feet)*
Glass fiber mulch	107	0.93
Polyethylene mulch	67	1.10
Control (no mulch)	52	.86

Test 4: Pits, Synthetic Mulches, and Simazine on Two Aspects, 1964

A second test of the glass fiber and polyethylene mulches was made at Zena Creek in 1964. It was believed that relative effects of the mulches, the weather and, perhaps, the interactions, could be gaged by using something other than a mechanical mulch to eliminate competing vegetation. The pre-emergence herbicide simazine was selected to provide this weed-free condition; it was assumed that simazine would not directly affect seedling growth. Thus, the four treatments were: (1) black polyethylene mulch; (2) glass fiber blanket mulch; (3) simazine herbicide application; and (4) control (no treatment other than the pit).

East and west aspects were again compared by using four replications on each aspect. Average soil depths on the eight plots ranged from 21 to 31 inches to bedrock. Two hundred seedlings were planted in each of the eight plots, 50 seedlings per treatment (total of 1,600 seedlings).

[6] "t" tests of mean heights showed no significant differences.

The hillside pits, 3 by 3 feet and about 6 inches deep in the center, were prepared shortly before the seedlings were planted in early June 1964. The glass fiber mats and polyethylene sheets were held in place by three, or more, 1-foot-long wire pins. Simazine pellets were scattered evenly at a rate of 5.67 grams per pit; the cost of herbicide per seedling was 3.2 cents. As a followup, live seedling tallies were made each fall through 1968.

Rainfall at the Zena Creek study area, June to September 1964, was 175 percent of normal (table 4). This exceptionally wet summer undoubtedly had a bearing on seedling survival patterns.

First-year survival was the highest of any comparable plantings at Zena Creek. Aspect differences were significant but treatment differences were not. Survival was greatest on the west aspect (Appendix II). Probably the generous recharging of soil moisture during the summer was a big factor in the relatively high survival when using black polyethylene mulch. This lateral recharging, coupled with the relatively cool summer of 1964, probably reduced the high temperature-moisture deficit impact of the black polyethylene, giving a slightly greater survival level than was found in the 1963 tests.

Black polyethylene improved survival on both aspects (fig. 6), but was the best treatment on the east aspect. Simazine also improved survival on both aspects; it was best on the west, more moist aspect. By 1968 all treatments on the east aspect appeared to be much more effective than those on the west aspect when measured against the no-mulch treatment. In 1968, however, treatments differed significantly ($p = 0.01$), as reflected by the following tabulation:

Treatment	*East*	*West*
	(Percent of survival)	
Control (no mulch)	28	61
Glass fiber mulch	42	60
Polyethylene mulch	55	66
Simazine	44	70

The range in treatment effects increases with time for both aspects, i.e., differences became more prominent with time (fig. 6). This fact underscores the cumulative effect of less advantageous conditions. The large increase in the range between 1965 and 1966 may be attributed to a dearth of rainfall between June and September (table 4). Total precipitation in these months was only 33 percent of normal.

Seedling heights were recorded in 1968, five growing seasons after planting. As previously mentioned, there were seedlings with damaged terminals on every plot, but one plot that was covered by grass on a warm southeast slope was especially hard hit and about 50 percent of the live seedling terminals were clipped, nipped or cut. On other plots where brush species predominated there were fewer damaged terminals. It seems that either the deer or elk, or both, may congregate in these warm, open areas where the snow is sometimes absent through the winter, or maybe it is shallower and melts earlier in the spring. Only a small amount of damage on the plots of Test 4 was attributed to rabbits and hares.

Table 4.--*Precipitation records*

Month	1959	1960	1961	1962	[illegible]	1964	[illegible]	[illegible]	1967	1968	average
					Deer Creek, [illegible]						
June	0.81	0.33	0.77	1.61	[illegible]	5.05	1.80	1.66	2.29	0.86	1.99
July	.20	.27	.07	.66	.18	1.15	.70	.05	.50	.50	.41
August	.94	.77	.83	.85	.34	1.73	1.74	.28	.10	2.12	.97
September	3.77	.94	.95	1.12	1.85	.86	2.14	1.63	1.71	.76	1.57
Totals	5.72	2.31	[illegible]	4.24	[illegible]	8.77	6.38	[illegible]	4.60	[illegible]	[illegible]
					Idaho City, [illegible]						
											Normal
June						2.93	[illegible]	0.22	1.83	[illegible]	[illegible]
July						[illegible]	.11	.02	.05	[illegible]	[illegible]
August						.82	1.78	[illegible]	[illegible]	[illegible]	.29
September						.57	1.66	.62	1.00		
Totals						[illegible]	[illegible]	[illegible]	2.88	[illegible]	[illegible]

[1]A standard U.S. Weather Bureau gage monitored by the Intermountain Forest and Range Exp. Station, Watershed Management Research work unit, Boise, Idaho.

[2]A U.S. Weather Bureau climatological station.

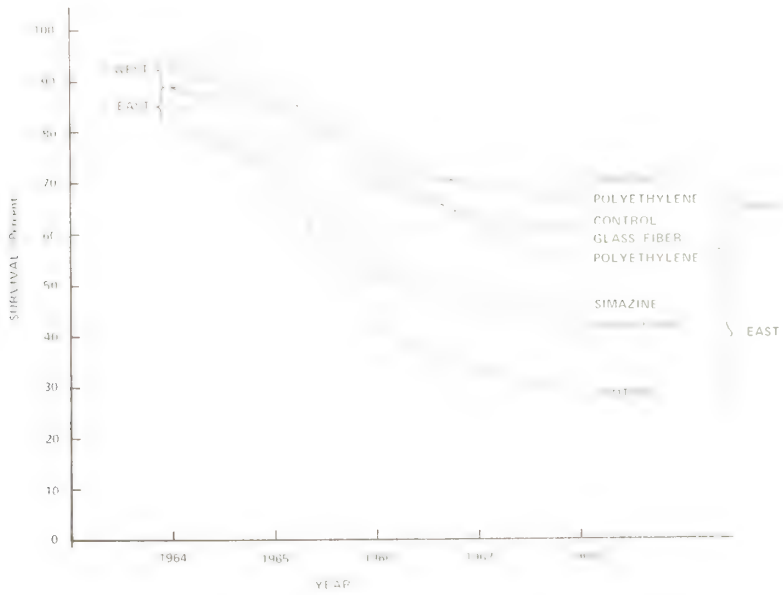

Figure 6.--Seedling survival by aspects and treatments, 1964 to 1968.

Average tree heights at the Zena Creek study area were greater for all treatments on the east aspect:

Treatment	*Tree heights*	
	East	*West*
	- - -(Feet)- - -	
Control (no mulch)	1.3	1.3
Glass fiber mulch	1.1	1.0
Polyethylene mulch	1.5	1.2
Simazine	1.3	1.1

Seedlings that received the black polyethylene mulch on the warmer aspect were consistently the tallest. Romberger (1963) has suggested that a threshold spring temperature triggers height growth. This increased height can be expected because higher temperatures occur over black surfaces and the threshold temperature is reached earlier in the spring when moisture is readily available.

Soil Moisture and Temperature Relations (Boise Basin)

Test 5: Soil Moisture and Temperatures Associated With Undisturbed Spots and Pits, With and Without Synthetic Mulches, 1964

These tests at the Boise Basin Experimental Forest attempted to accomplish the following.

(1) Trace the seasonal soil moisture depletion cycle under: (a) two kinds of mulch--black polyethylene, and glass fiber blanket; (b) weeded mineral soil; and (c) an undisturbed condition (control).

(2) Measure the summer temperature gradients on a given day above each of the four treatments on both level and sloping ground.

(3) Measure the seedling survival associated with the treatments, soil moisture, and the air temperature regime.

Survival results were analyzed for two test areas: (a) An aspect having an azimuth of 185° and a slope of 35 percent; and (b) an aspect at 223° with a slope of 32 percent.

Undamaged, 2-0, ponderosa pine planting stock with a top:root ratio of 1:2, or better, was planted in mid-May 1964. The mulches were put in place several days later. First-year survival was recorded at 2-week intervals from June 1 to October 15. The weeding treatment was repeated at each of the first five semimonthly survival counts. Annual survival counts were made each fall until 1968.

Precipitation at Idaho City in June and August of 1964 was more than twice the normal amount; July and September were very close to normal (table 4).

HALL, DALE O.

1971. Ponderosa pine planting techniques, survival, and height growth in the Idaho Batholith, USDA Forest Serv. Res. Pap. INT-104, 28 p., illus.

Site preparation and mulching tests were carried out on some steep slopes with shallow soils in the Douglas-fir--Ninebark habitat type. Five-year survival and height growth were measured. All treatments increased seedling survival. Height growth was positively correlated with plot survival percent and soil depth. Extensive mammal damage was noted.

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On July 1, 1964, 45 days after planting of seedlings, the soil moisture percent (dry weight) generally exceeded "field capacity" as estimated from 1/3 atmosphere tests in the laboratory (figs. 7 and 8; Appendices IV and V). Moisture contents were well above "field capacity" in the second area (B) and near "field capacity" in the first area (A). Soil moisture was determined at three levels below the surface: 3 to 6 inches, 9 to 12 inches, and 15 to 18 inches. In all samples, the hand-weeded plots appeared to show the greatest moisture recharge on September 1. Recharge was considerably less (or slower) under both polyethylene and glass fiber mulches. In some cases a recharge was not evident until the measurement of October 1. Such a recharge undoubtedly stemmed from lateral movement of soil water under the mulches.

Temperature profiles (°F.) at the Boise Basin study area were determined on August 4, 1964. Maximum air temperature recorded at the Weather Bureau Station at Idaho City on this date was 91°; the minimum was 40°. The sun was at its zenith between 12:40 and 12:45 p.m., m.s.t. Relative humidities ranged from a high of 84 percent to a low of 18 percent. The wind had an average velocity of 10 miles per hour and was out of the west. There were no clouds that day.

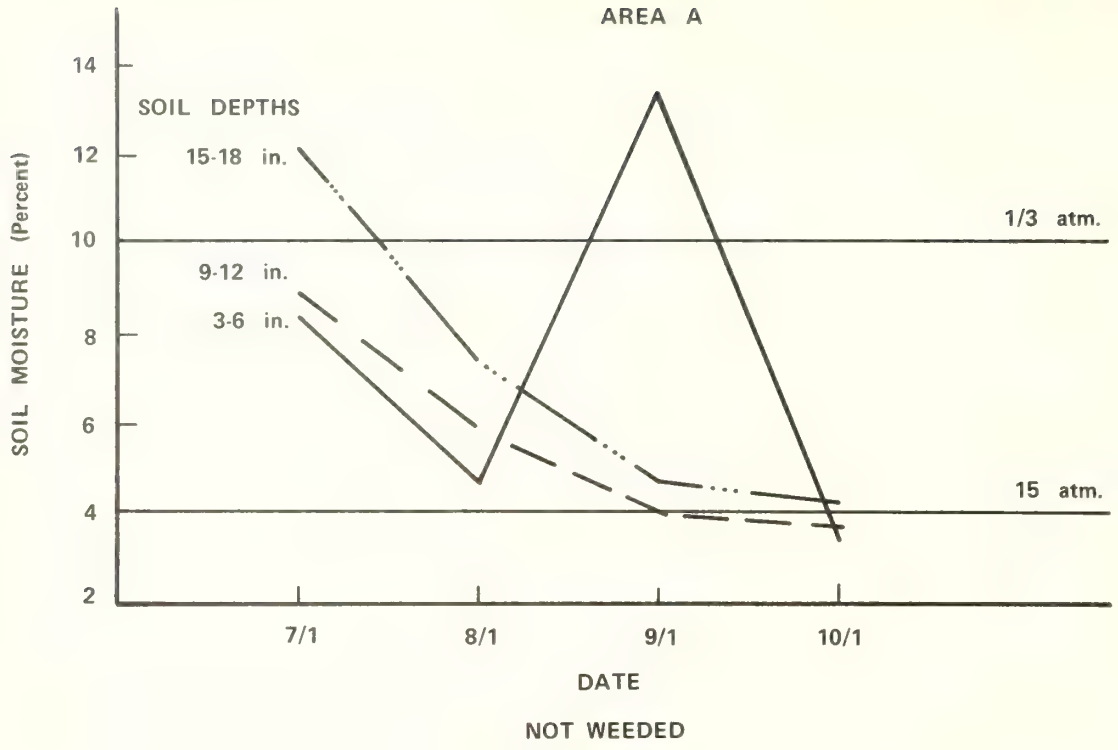
Temperatures were slightly higher on the slopes that were most nearly at right angles to the sun. Highest temperatures occurred at the soil surfaces (100.8° to 149.5° F.). Temperatures between the surface and 0.5 foot above the surface were highest over black polyethylene (149.5° to 96.5° F.). Glass fiber had the lowest maximum surface temperatures. Highest temperatures were reached sooner on the surfaces than above them.

Live seedling tallies were made on the 1st and 15th of each month from June to October 1964. The first mortality was noted July 15 (table 5). Fall tallies were continued annually until 1968 (Appendix II). The variation in survival of seedlings due to areas was amazingly low (Appendix VI). Treatments differed significantly ($p = .95$) in 1964 and 1965, but not in the remaining years. The undisturbed treatment had the poorest rate of seedling survival in all years. Through 1965, the other three treatments showed some differences as to seedling survival. In 1966, and later, the yearly differences in survival were slight; this apparently was the reason for a lack of significance in the treatments during these years.

Table 5.--*Seedling survival (percent) by treatments, July to October 1964, Test 5*

Treatment	Date of seedling tally					
	7/15[1]	8/1	8/15	9/1	9/15	10/1
Glass fiber mulch	100	100	100	100	100	100
Polyethylene mulch	100	100	100	96	94	92
Hand weeded	100	100	96	92	90	86
Control (no mulch)	98	98	92	86	82	82

[1]25 seedlings planted in each cell.



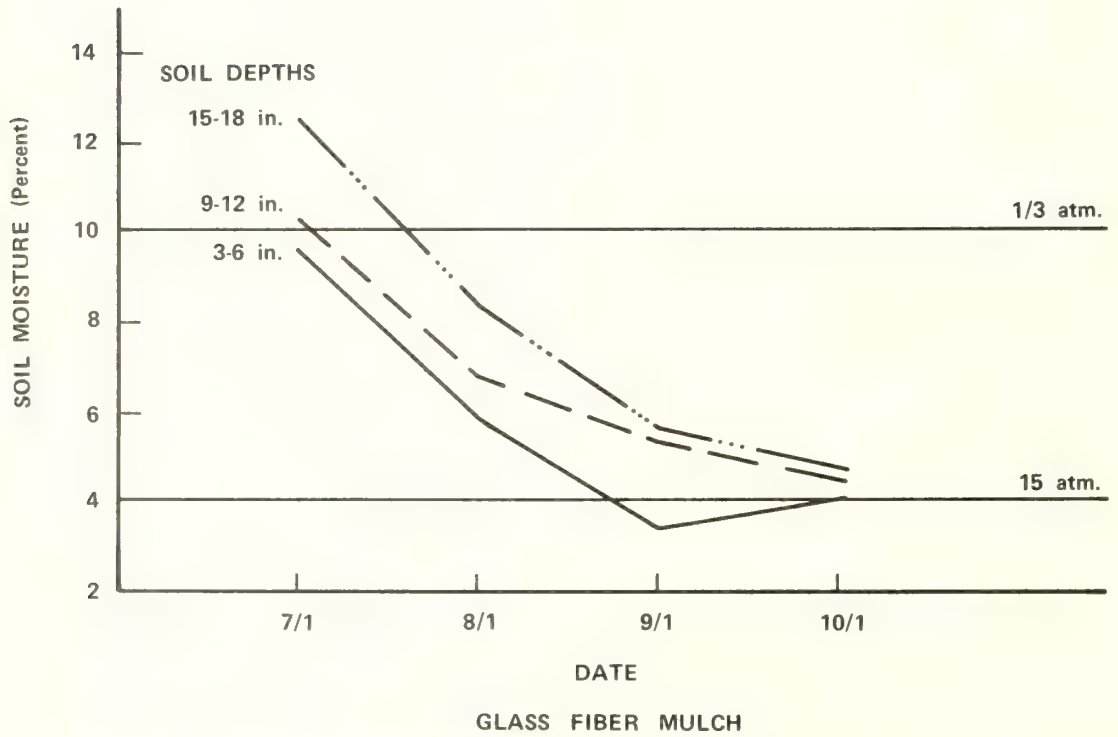


Figure 7A.--Periodic monthly soil moisture levels under two treatments.

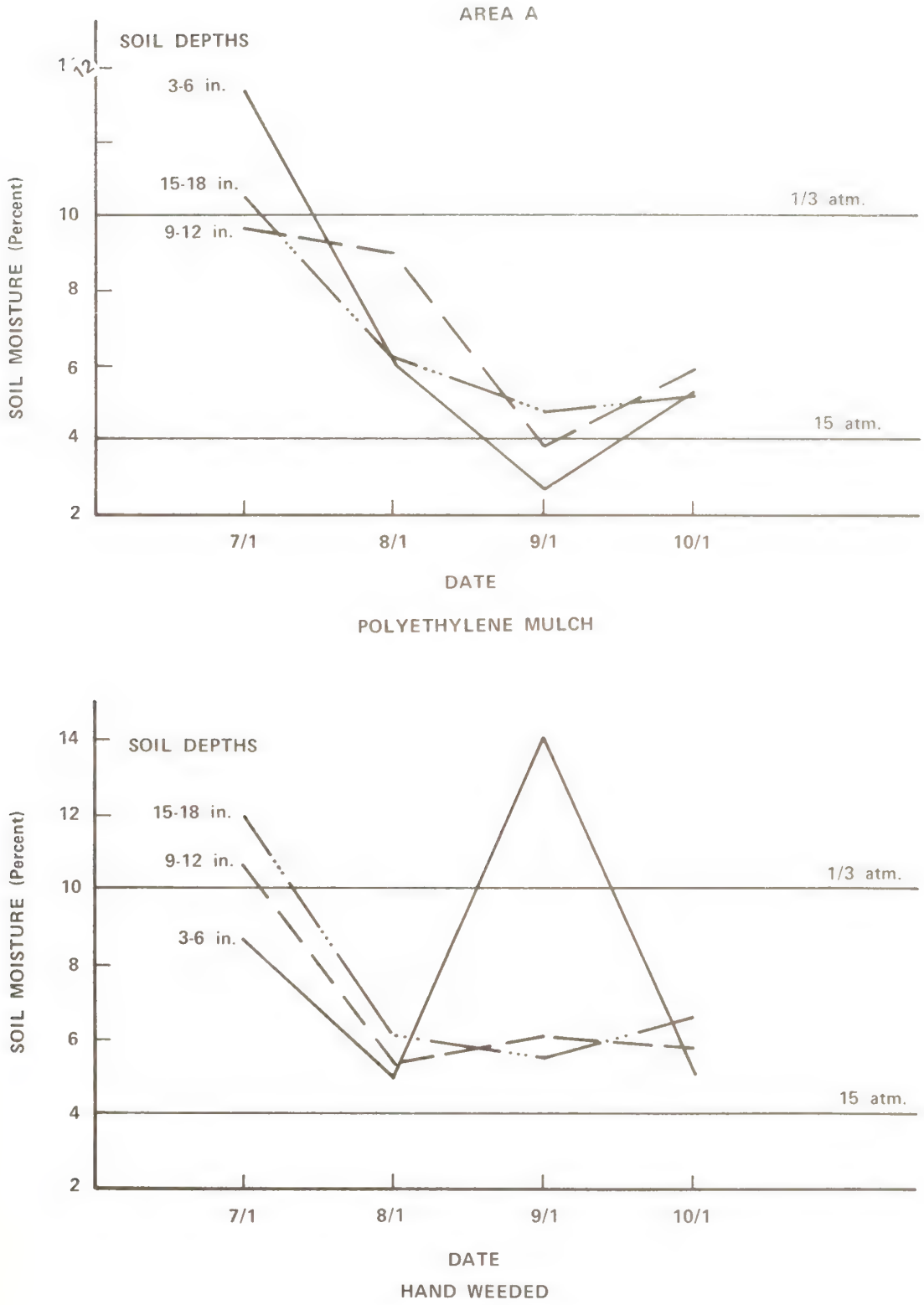


Figure 7B.--Periodic monthly soil moisture levels under two treatments.

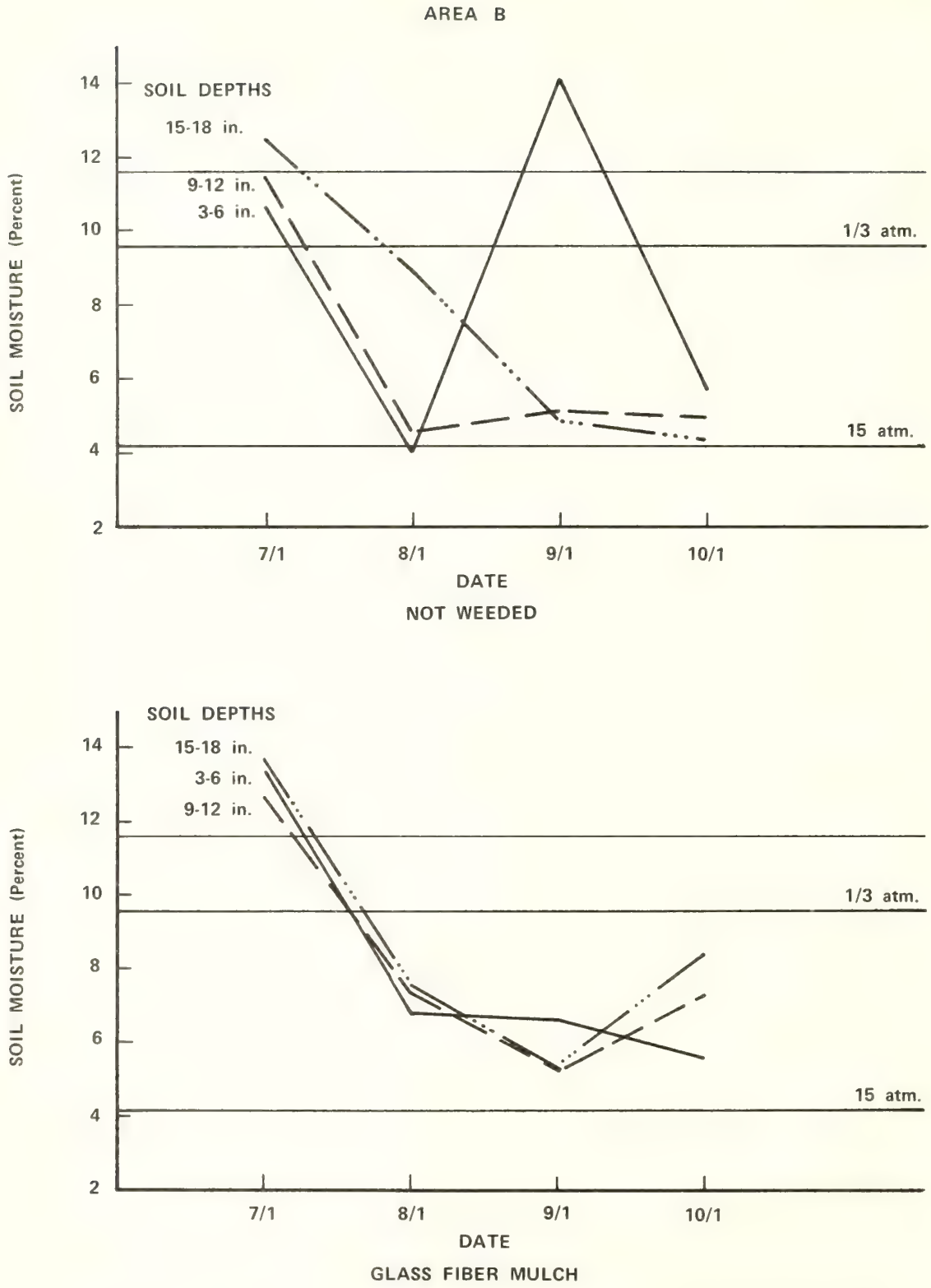


Figure 8A.--Periodic monthly soil moisture levels under two treatments.

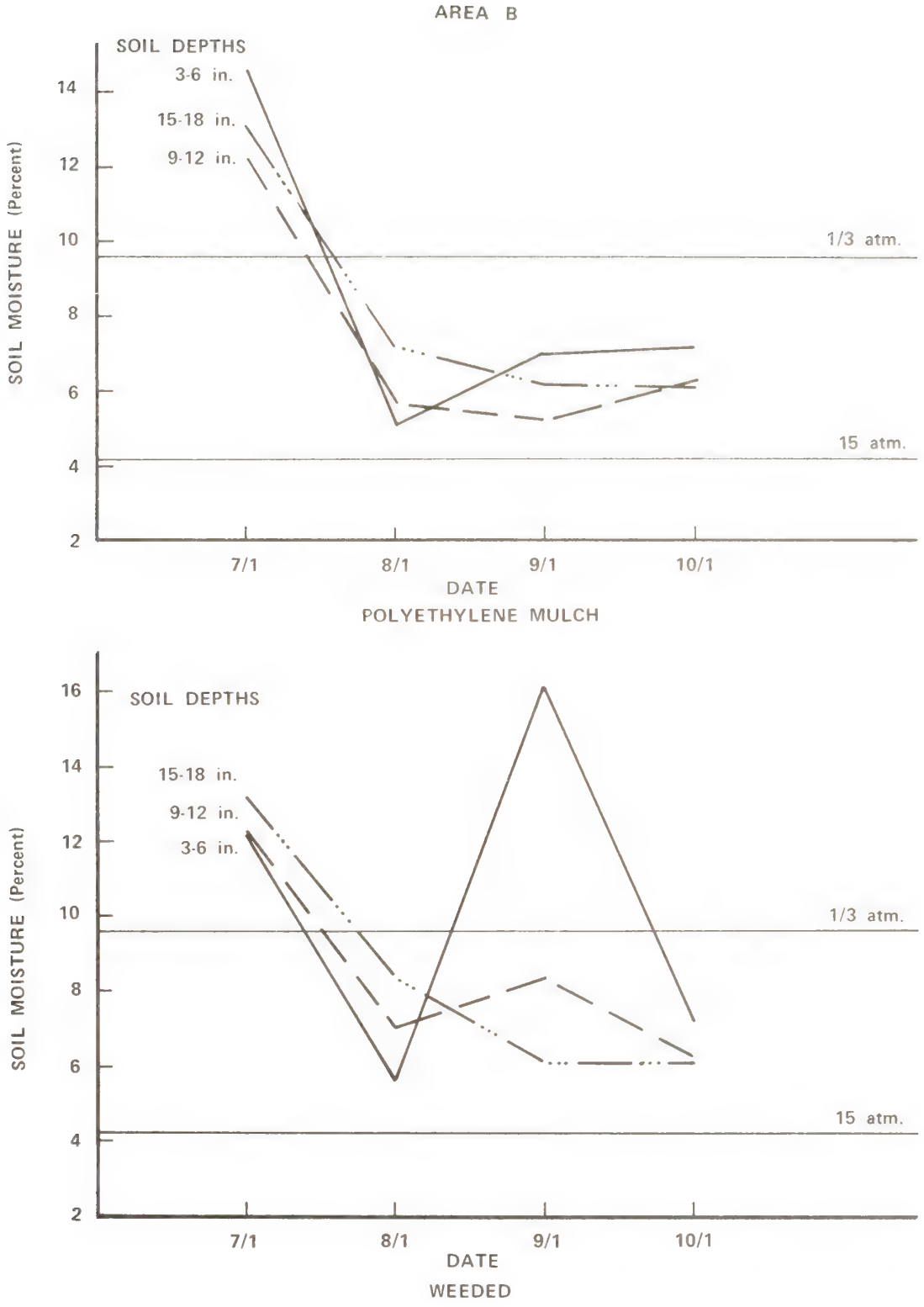


Figure 8B.--Periodic monthly soil moisture levels under two treatments.

This trend of diminishing significance at the Boise Basin study area is in direct contrast to the increasing significance for the 1964 plantings at Zena Creek. Approximately one-third of the total variation in this Boise Basin test was caused by sampling error, and only a negligible variation existed between experimental units (Areas). This originally negligible variation increased with time, at a faster rate than treatment variation, thus giving the opposite trend in "F" values.

The interrelationships between the mulch temperatures on a day in August and soil moisture relationships are not easily identified. The high temperatures that occurred over the polyethylene apparently did not reduce seedling survival to any great extent in this summer of abundant rainfall. Likewise, the slower recharge rate under this mulch was not limiting to any noticeable degree. More moderate conditions associated with the glass fiber blanket did not provide significantly better survival during the 5-year period.

Indicating the advantages of less competition and earlier spring height growth initiation, seedlings mulched with black polyethylene film were taller. As mentioned earlier, significant numbers of the seedlings alive in 1968 had terminal damage (table 6).

The impact of vegetative competition was evident and seedlings that received the control treatment were the shortest in both terminal damage classes (fig. 9). A comparison of the means within damage classes showed a significant difference ($p = .05$, "t" test) only between the polyethylene and control treatments, and this difference was in the "damaged" terminal class. Although the mean for the weeded treatment was the same as the mean for the polyethylene the greater variation about the former made the comparison with the control treatment insignificant ($p = .05$). These results imply that the use of mulch to reduce competition does provide some increased height growth.

Table 6.--*Proportion (percent) of seedling terminals damaged, 1964 to 1968*

Treatment	Area "A"	Area "B"	Average
		Percent	
Polyethylene mulch	37	18	28
Glass fiber mulch	20	32	26
Hand weeded	26	37	32
Control (no mulch)	35	60	47

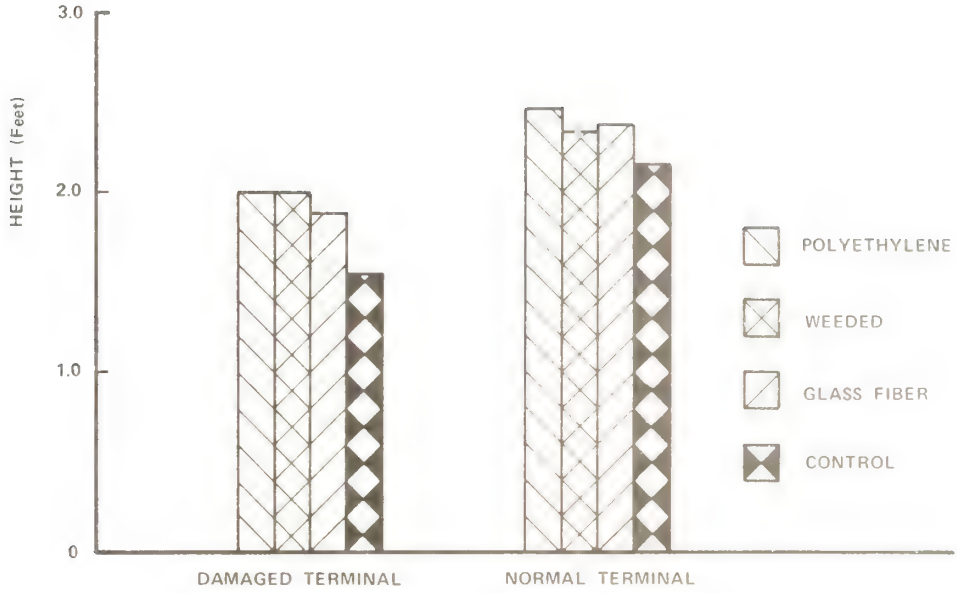


Figure 9.--Mean fifth-year heights of seedlings by treatment and terminal damage classes.

Summary and Conclusions

During the period from 1962 to 1964, ponderosa pine seedlings were outplanted in four different tests at Zena Creek, Payette National Forest and one test (1964) at Boise Basin Experimental Forest, Boise National Forest. All tests appear to have been in the Daubenmires' (1968) Douglas-fir--Ninebark h.t. A variety of techniques to reduce or eliminate competition were tested. Site preparation tests included scalps (from 2 to 6 feet wide), pits, furrows, burning, and natural undisturbed areas. For the mulch tests, black polyethylene film, glass fiber blankets, and straw were used. Simazine, a pre-emergence herbicide, was also tested. Some limited attempts were made to characterize the site conditions and evaluate seedling responses to: aspect; soil depth and moisture content; and summer precipitation and temperature. Seedling survival tallies were made throughout a 5-year period after each planting (Appendix II). Fifth-year height measurements were made on a number of plots. Some general conclusions are warranted:

1. All the practices which reduce vegetative competition improved survival. The relative improvement increased with time.

2. The better the survival the taller the trees in the fifth year when other factors are held constant.

3. The greater the summer precipitation (with good distribution over a period of time), the better the survival.

Some additional conclusions were made as a result of individual tests. Naturally, these conclusions are limited to the Douglas-fir--Ninebark h.t. in the Idaho Batholith. The tests were not specifically designed to obtain some of the conclusions, but the observations and results from the series seem to support them. Confidence in these conclusions is indicated as follows: * = statistically significant test assuming

that p = .95; trends = one or more tests appear to support conclusions, but because of time limits, confounding variables, or design limitations, no statistical significance was obtained; observed = no measurements were made but the relationship seemed apparent during field observations. The latter two classes should be accepted cautiously until proper testing or extensive experience validates them. The conclusions are as follows:

1. Seedling survival and height growth is positively correlated with soil depth (Tests I, III, V: trends).

2. Animal damage is extensive (up to 82 percent) and affects both survival and height attainment (I, III to V: trends).

3. Hand scalping with an application of simazine provided the least expensive control of competition in a moist summer--1964 (IV: trends).

4. Northwest aspects have better survival (IV: *; III: trends), but fifth-year heights are greater on warmer southeast aspects (III, IV: trends).

5. Treatments have less influence on survival in the more moist seasons and sites (III to V: trends).

6. Native grass competition (moderate density levels) seem less severe on seedling survival than brush species in this h.t. (III, IV: observed).

7. Animal damage did not appear to be influenced by mulch materials (I, III to V: trends).

8. Mean fifth-year heights for undamaged seedlings ranged from 0.86 to 2.50 feet. Heights appeared to be positively correlated with survival, soil depth, and relative temperatures (I, III to V: trends).

9. Five-year heights were greater when black polyethylene was used (III to V: trends).

10. On granitic soils in central Idaho the surface 12 inches of soil reaches the "wilting point" (15 atmospheres determination) during the summer unless additional moisture comes from summer storms (V: trends).

Recommendations

As a result of these studies, the following two recommendations seem appropriate.

1. Initial seedling stocking standards should take into account the onsite differences and be adjusted as to the planting area to insure adequate stocking at some target date after planting, for example, 3, 4, or 5 years. The survival rates vary greatly with the onsite environment, i.e., specific cover species, aspect, soil depth, animal populations, and summer precipitation. The probabilities of abnormal summer precipitation levels should be used to weight the initial standard. Sites similar to those in these studies may require planting 600 seedlings, or more, to have 300 live seedlings after 3 years.

2. Site preparation and vegetation control should be used to improve ponderosa pine seedling survival and growth. On steep slopes in habitat types similar to this study, 3- to 4-foot-wide scalps (hand-made) with a simazine herbicide treatment (6 grams/10 sq.ft. for simazine 4G) in the fall should lead to reasonable survival levels. Planting unprepared sites would require 3 to 4 times as many seedlings, and a corresponding cost increase, to reach a 3-year stocking standard.

Natural regeneration was not considered in these tests. Because of the inherent problems of planting seedlings in the shallow soil of these steep slopes, and because of the high costs, a third recommendation is advisable, as follows:

3. Further study should include comparisons with natural regeneration systems.

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Appendix I

Soil Depths on Regeneration Plots, Test 1

Area summary

Test area	Block number	Number of soil pits	Soil depth to bedrock, average (*Inches*)
1	1	3	12.3
	2	7	16.4
	3	6	20.1
	Total	16	[1]17.0
2	4	6	19.8
	5	5	28.8
	6	6	23.2
	Total	17	23.6
Combined 1 and 2		33	20.4

Treatment summary

Treatment	Test area number	Number of soil pits	Soil depth to bedrock, average (*Inches*)
		STRAW MULCH	
Scalp	1	3	24.3
	2	3	25.3
	Total	6	24.8
Pit	1	3	11.0
	2	3	22.3
	Total	6	16.7
Furrow	1	2	16.0
	2	3	25.7
	Total	5	21.8
		NO MULCH	
Scalp	1	3	19.3
	2	3	29.3
	Total	6	24.3
Pit	1	4	18.8
	2	4	25.2
	Total	8	22.0
Furrow	1	5	20.0
	2	3	19.7
	Total	8	19.9
Treatments	1	[2]20	18.6
	2	[2]19	24.6
	Total	[2]39	21.5

[1]This column consists of weighted averages.

[2]Some borderline pits used for two treatments so number of pits will not agree with total in block summary.

Appendix II

Survival (Percent), Tests 1 through 4[1]

	1962	1963	1964	1965	1966	1967	1968
-TEST 1-							
Test area I			*Percent*				
No mulch							
Scalps	62.3	50.7	46.4	43.5	36.2	--	--
Pits	64.0	52.0	45.3	36.0	25.3	--	--
Furrows	77.3	66.7	56.0	45.3	20.0	--	--
Straw mulch							
Scalps	69.3	57.3	52.0	48.0	22.7	--	--
Pits	57.5	42.5	39.7	32.9	27.4	--	--
Furrows	59.3	42.9	30.0	22.9	21.4	--	--
Test area II							
No mulch							
Scalps	58.6	47.1	38.6	34.3	30.0	--	--
Pits	61.3	52.0	36.0	22.7	16.0	--	--
Furrows	64.0	46.7	32.0	24.0	20.0	--	--
Straw mulch							
Scalps	78.3	68.9	48.6	41.9	37.8	--	--
Pits	70.4	57.7	54.9	50.7	36.6	--	--
Furrows	77.3	69.3	53.3	42.7	34.7	--	--
-TEST 2-							
East			*Percent*				
2' Scalps	63.6	63.5	54.5	45.5	27.3	--	--
4' Scalps	100.0	80.0	80.0	80.0	60.0	--	--
6' Scalps	66.7	50.0	33.3	33.3	33.3	--	--
Burned spots	83.4	83.4	83.4	83.4	55.6	--	--
West							
2' Scalps	67.2	57.0	53.5	50.0	41.4	--	--
4' Scalps	75.5	67.6	63.1	60.0	50.8	--	--
6' Scalps	76.2	67.7	52.5	52.5	40.7	--	--
Burned	66.2	63.1	61.5	61.5	58.5	--	--
TEST 3-							
East			*Percent*				
Scalped	61.3	38.9	31.5	20.1	116.1	--	--
Glass fiber	76.0	64.0	57.3	48.0	43.3	--	--
Polyethylene	34.7	29.3	27.3	23.3	22.0	--	--
West							
Scalped	60.7	53.3	47.3	33.8	31.1	--	--
Glass fiber	85.3	74.7	69.4	54.2	47.9	--	--
Polyethylene	50.7	43.0	37.8	31.5	30.1	--	--

(Con. next page)

	1962	1963	1964	1965	1966	1967	1968
-TEST 4-							
East			*Percent*				
Scalped	--	--	81.5	73.0	41.0	33.5	27.5
Glass fiber	--	--	83.0	73.5	51.5	45.0	41.5
Polyethylene	--	--	89.0	83.0	63.0	58.5	54.5
Simazine	--	--	86.0	77.5	53.0	48.5	43.5
West							
Scalped	--	--	89.5	85.0	69.5	63.0	61.0
Glass fiber	--	--	92.0	81.5	70.5	61.0	60.0
Polyethylene	--	--	93.5	88.5	73.5	68.5	66.0
Simazine	--	--	94.0	90.0	75.0	70.0	70.0
-TEST 5-							
Test area I			*Percent*				
Weeded	--	--	84	80	80	76	76
Glass fiber	--	--	100	84	84	80	80
Polyethylene	--	--	92	83	88	80	76
Undisturbed	--	--	80	68	64	64	64
Test area II							
Weeded	--	--	88	84	76	76	76
Glass fiber	--	--	100	92	76	76	76
Polyethylene	--	--	92	84	76	76	68
Undisturbed	--	--	84	72	64	60	60

[1]Highest values underlined.

Appendix III

Mean Heights of Seedlings by Terminal Condition Class, 1968, Test 1

Test area	No mulch						Straw mulch						Means	
	Scalps		Pits		Furrows		Scalps		Pits		Furrows			
	Height	No.	Height	No.	Height	No.	Height	No.	Height	No.	Height	No.	Height	No.
	Feet													
NORMAL TERMINAL														
1	1.60	5	1.27	7	1.23	3	1.15	8	1.21	7	.90	3	1.24	33
2	1.40	2	1.40	3	2.00	4	1.30	1	2.08	8	.75	2	1.72	20
Mean	1.54	7	1.31	10	1.67	7	1.17	9	1.67	15	.84	5	1.42	53
DAMAGED TERMINAL														
1	1.22	14	1.14	11	.81	8	.90	7	1.32	6	1.00	3	1.10	45
2	1.29	17	1.42	6	1.43	8	1.58	25	1.34	17	1.49	20	1.44	93
Mean	1.26	31	1.24	17	1.13	16	1.51	28	1.33	23	1.43	23	1.33	138
											G Mean		1.35	191
											Area 1		1.16	78
											Area 2		1.49	113

Appendix IV

Soil Moisture Content (Percent) at 1/3 and 15 Atmospheres, Test 5

Area	Area "A" Upper slope	Area "A" Lower slope	Area "B" Upper slope	Area "B" Lower slope
	15-ATMOSPHERE TEST			
Inches	*Percent*			
3-6	3.85	3.78	4.99	4.83
9-12	4.36	3.61	3.89	4.34
15-18	4.46	4.21	3.60	3.92
Mean	4.05		4.26	
	1/3-ATMOSPHERE TEST			
3-6	10.34	9.94	9.93	11.49
9-2	9.36	9.62	8.26	10.18
15-18	10.32	10.74	8.01	9.85
Mean	10.05		9.62	

Appendix V

Periodic Monthly Soil Moisture Content Under Four Mulch Treatments at Three Depths, Test 5

Treatment	Depth	Date							
		7/1	8/1	9/1	10/1	7/1	8/1	9/1	10/1
	Inches	- - - - - - - - - - - - - - - - *Percent* - - - - - - - - - - - - - - - -							
Black polyethylene	3-6	13.4	6.1	2.7	5.3*	14.6	5.1	7.0	7.2*
	9-12	9.7	7.0	3.9	5.4*	12.3	5.7	5.3	6.3*
	15-18	10.5	6.2	4.8	5.1*	13.1	7.2	6.2	6.1
Glass fiber	3-6	9.6	5.8	3.4	4.1*	13.4	6.8	6.7	5.6
	9-12	10.3	6.8	5.3	4.5	12.7	7.4	5.3	7.4*
	15-18	12.5	8.4	5.7	4.8	13.7	7.6	5.4	8.5*
Hand weeded	3-6	8.7	5.0	14.1*	5.1	12.1	5.7	16.1*	7.2
	9-12	10.6	5.4	6.1*	5.8	12.3	7.0	8.3*	6.2
	15-18	12.0	6.1	5.5	6.6*	13.2	8.4	6.1	6.1*
Not weeded	3-6	8.4	4.7	13.4*	3.5	10.7	4.0	14.2*	5.7
	9-12	8.7	5.9	4.0	3.7	11.5	4.6	5.2*	5.0
	15-18	12.1	7.3	4.7	4.2	12.5	7.0	4.9	4.4

* Indicates some recharge since last date.

Appendix VI

Analysis of Variance Table for Rolling Dowsing, 1964-1968, Test 6

Component	d.f.	1964 SS	1964 MS	1964 F	1965 SS	1965 MS	1965 F	1966 SS	1966 MS	1966 F	1967 SS	1967 MS	1967 F	1968 SS	1968 MS	1968 F
Area	1	0.00	0.00	0.00 NS	0.02	0.02	0.10 NS	0.24	0.24	1.00 NS	0.04	0.04	0.10 NS	0.08	0.08	0.05 NS
Location	48	4.44	.09		10.00	.20		11.96	.24		13.66	.28		12.73	.26	
Treatment	3	.77	.25	3.12*	1.12	.37	3.08*	1.09	.36	2.40 NS	1.25	.41	2.56 NS	1.12	.37	2.11 NS
T x A	3	.01	.00	.00 NS	.06	.01	.08 NS	.13	.04	.27 NS	.05	.01	.16 NS	.08	.02	.11 NS
Error	144	11.96	.08		18.31	.12		22.52	.15		23.94	.16		26.29	.18	
Total	199	17.19			29.51			35.95			38.95			40.31		

Headquarters for the Intermountain Forest and Range Experiment Station is in Ogden, Utah. Field Research Work Units are maintained in:

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Logan, Utah (in cooperation with Utah State University)
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Moscow, Idaho (in cooperation with the University of Idaho)
Provo, Utah (in cooperation with Brigham Young University)

VEGETAL DEVELOPMENT FOLLOWING PRESCRIBED BURNING OF DOUGLAS-FIR IN SOUTH-CENTRAL IDAHO

by L. Jack Lyon

USDA Forest Service Research Paper INT-105, 1971
INTERMOUNTAIN FOREST AND RANGE
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L. Jack Lyon, Wildlife Research Biologist, has been leader of the research work unit devoted to ecology and management of wildlife habitat since 1962. This unit is headquartered at the Forestry Sciences Laboratory on the campus of the University of Montana. From 1955 to 1961, Dr. Lyon was a Research Biologist for the Colorado Game and Fish Department. His studies in postfire forest succession are widely recognized as a unique and continuing contribution to the understanding of seral vegetation dynamics. Consequently, he is a recognized authority on ecological succession and wildlife-vegetation relations of forest habitats. Dr. Lyon holds both a B.S. and an M.S. degree in Wildlife Management from Colorado State University, as well as his Ph.D. degree in the same field from the University of Michigan. He has authored over 25 technical publications and articles. He is a life member of the Wildlife Society and a member of the American Institute of Biological Sciences, American Association for the Advancement of Science, and Ecological Society of America.

ABSTRACT

One-hundred and twenty acres of standing Douglas-fir timber in Neal Canyon, near Ketchum, Idaho, were burned with prescribed fire on August 1, 1963. This paper presents descriptions of the fire, the prefire forest community, and the first 7 years of postfire vegetal development. Effects on wildlife habitat are stressed.

The Neal Canyon prescribed fire was burned during daylight hours under conditions severe enough to produce crown fire in the timber. Measurements of heat flux were comparable to measurements taken in slash fires with 15 to 20 tons of fuel per acre and fine fuel moisture near 5 percent. All litter and herbaceous plants, all dead woody stems under 3 inches in diameter, and all live stems under 2 inches were completely consumed.

After seven growing seasons, the early seral herbaceous community contains nearly twice as many species as the preburn community. Virtually all the perennial herbaceous species resprouted and many new species have appeared. Postfire canopy cover has never dropped significantly below preburn levels.

The Douglas-fir overstory was killed in the fire, but a new forest has been established by planting, direct seeding, and some natural seeding. Canopy closure of the tree overstory is predicted before the thirtieth year.

Most of the shrub species recorded in the community before the fire have resprouted, but the relative importance of several species has been significantly modified. Crown volume per acre of Rocky Mountain maple *(Acer glabrum)* was greater than all other shrub species before the fire. During the first 7 postfire years, however, Scouler willow *(Salix scouleriana)* and maple have been about equal in crown volume, and it is predicted that crown volume per acre of snowbrush *(Ceanothus velutinus)* will surpass all other shrub species by succession year 9.

The Neal Canyon prescribed fire was judged to be successful in all respects. Silvicultural objectives were achieved, wildlife habitat was significantly improved, and there was no apparent watershed damage. A theoretical model is presented to show that the preburn forest community description can be used to predict postfire community structure and long-term development pattern.

USDA Forest Service
Research Paper INT-105
August 1971

VEGETAL DEVELOPMENT FOLLOWING PRESCRIBED BURNING OF DOUGLAS-FIR IN SOUTH-CENTRAL IDAHO

by L. Jack Lyon

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FOREWORD

In 1966, preliminary results of this study were reported by Lyon in Research Paper INT-29, *Initial Vegetal Development Following Prescribed Burning of Douglas-fir in South-Central Idaho*. Because of a misplaced decimal point in that report, data for density and volume of shrubs 2 years after the fire are incorrect. Although the conclusions presented remain essentially valid for the first 2 years following the fire, this paper is intended to replace rather than supplement the original.

INTRODUCTION

Prescribed fires in logging slash are not unusual in the forests of the northern Rocky Mountains. Burning is an effective means of reducing wildfire hazard and preparing timber sites for regeneration. Fires in standing timber, on the other hand, have become relatively uncommon in this age of smokejumpers, retardant bombers, and fast transportation; even though uncontrolled forest fires do occur occasionally, it is impractical to plan studies of specific forested areas that might be burned. The probability of a burned area large enough for study is low, and at best the occurrence of wildfire on areas marked for study would be extremely fortuitous. Thus, when personnel of the Sawtooth National Forest intentionally burned 120 acres of standing Douglas-fir on the first day of August 1963, the situation was virtually unique.

The basic objectives of this prescribed fire were sanitation and site preparation for silvicultural purposes. A stand of Douglas-fir in Neal Canyon on the Ketchum Ranger District had been selectively logged twice between 1950 and 1960. The remaining trees were mostly mistletoe-deformed saplings and poles. After the diseased trees were burned, parts of the area were planted and parts were direct-seeded to establish a new and healthy timber stand.

From a research standpoint, this fire presented a significant opportunity to accomplish the following: measure the heat output of a fire similar to an uncontrolled forest fire; investigate the influence of a prefire plant community on postfire vegetal development; and evaluate the postfire plant community as wildlife habitat. This paper is a report on the fire and the first 7 years of postfire vegetal development.

Figure 1. — Main study site, Neal Canyon prescribed fire area, July 1963.

Neal Canyon is a small drainage off Eagle Creek and the Big Wood River about 6 miles north of Ketchum, Idaho. The 120-acre burned area is 1.5 miles east of U. S. Highway 93 in the northeast quarter of Section 13, Township 5 North, Range 17 East, Boise Meridian. Since some parts of the area had been heavily disturbed during logging, the specific study site selected for both prefire and postfire examination was a 20-acre patch of less-disturbed terrain on the lower middle slope (fig. 1). The true aspect of this study site is N 10-20° E; the slope is 64 percent, and the elevation is 6,500 feet.

In addition to this specific study site, we established three other subsites within the burn for comparison of postfire vegetal development rates. One of these sites is essentially a replicate of the intensive site, but the other two are higher on the hill in areas that are somewhat steeper, rockier and had considerably fewer trees prior to burning (fig. 2).

In this part of Idaho, summers are cool and winters rigorous. Annual precipitation at the Hailey and Sun Valley weather stations is 14 to 17 inches, most of which falls in the winter. Total snowfall at the two stations averages 85 and 120 inches, respectively. In an average year, maximum temperatures over 90° F. are recorded for only 7 to 15 days while temperatures below 32° F. are recorded for 206 to 288 days. Record minimum temperatures for the respective stations are -36° F. and -46° F. (U. S. Dep. Commerce 1964).

Forested sites in the Sun Valley area are generally confined to north- and east-facing slopes, and vegetation is characterized by abrupt changes associated with aspect, altitude and slope. Douglas-fir *(Pseudotsuga menziesii)*

Figure 2.—Mid-slope and riparian zone in the Neal Canyon watershed, looking south.

is the most important tree species. Lodgepole pine *(Pinus contorta)* is common and subalpine fir *(Abies lasiocarpa)*, Engelmann spruce *(Picea engelmannii)*, and patches of aspen *(Populus tremuloides)* are often associated with mesic microsites. Vegetation beneath the mature forest is highly variable, but is often dominated by Rocky Mountain maple *(Acer glabrum)* and snowberry *(Symphoricarpos oreophilus)* as illustrated in figure 3. On dry south slopes and valley bottoms, vegetation ranges from sagebrush grassland to mixed forb communities.

Soils in Neal Canyon are of both igneous and sedimentary origin although the prescribed burn is confined to an area thinly overlaid with latite and horneblende andesite (Umpleby, Westgate, and Ross 1930). Within the drainage, soils are rocky, poorly developed, and highly stable. Mechanical analyses of representative samples show at least 50 percent gravel and a shift from sandy loams on the surface to a sandy clay loam below 14 inches. Further evidence of soil stability is provided by a sheep driveway in Eagle Creek where overgrazing has caused plant community changes but very little surface erosion.

Wildlife use of Neal Canyon has not been studied in detail although we have observed some evidence of browsing and big game tracks during summer fieldwork. Fifty elk were planted at Ketchum between 1934 and 1936, and the management unit for the Big Wood River supported about 600 elk in 1965 (Tanner 1965). Because of deep snow, Neal Canyon is probably not accessible during the critical winter period, but elk apparently do use the area in the spring and deer probably use it all summer.

Figure 3. -- Two views of representative vegetation within the Neal Canyon prescribed fire area, July 1963.

Vegetation Sampling

In the preburn examination of the Neal Canyon forest community, vegetation was divided into five life-form groups:

Trees — over 4.5 feet tall
Subtrees — 1.5 to 4.5 feet tall
Tall shrubs — over 8 feet tall
Low shrubs — 1.5 to 8 feet tall
Herbaceous — all herbaceous vegetation and woody plants under 1.5 feet tall

Herbaceous vegetation and woody plants under 18 inches (including tree seedlings) were recorded in a series of 25 systematically spaced 2- by 2-foot quadrats. Species were listed for each plot, and ground cover was estimated to the nearest square foot. In those cases where a single plant species covered one-fourth or more of the plot, cover data were recorded by species.

Density of woody plants over 18 inches high was estimated using an angle-method[1] version of the quarter-sampling techniques proposed by Cottam and Curtis (1956) and modified by Morisita (1957). From each of 20 points spaced at approximately 50-foot intervals, we measured the distance in each quadrant to the nearest tree, the nearest subtree, the nearest tall shrub, and the nearest low shrub. Distance measurements were corrected to horizontal within the upslope and downslope quadrants.

Trees were categorized by diameter class, and shrub size was determined by measuring two diameters (d_1 d_2) and the height (h) of the plant crown. In subsequent calculations, these measurements were converted to elliptical canopy areas,

$A = \frac{\pi\, d_1\, d_2}{4}$ and to cylindroid volumes, V=Ah.

During the first 2 years following the fire we continued to use quarter-method sampling, but analyses of these data made it apparent that distance techniques were entirely inadequate for the low-density postfire plant community under examination. Despite the 50-foot spacing between sampling points, identical shrubs were sometimes recorded at two or even three consecutive points. Accordingly, in 1966, we located and permanently marked 20, 0.04-acre circular plots on the approximate locations of the quarter-method sampling points. The 2- by 2-foot quadrats were also permanently located and marked with short metal rods.

Because so many shrubs had been recorded at more than one point in the distance measurements, it was possible to plot individual plants by triangulation and create circular-plot data to replace the quarter-method samples of 1964 and 1965. However, the 1963 preburn data included almost no double sampling on the same plants and no attempt was made to replot these data.

Each of the three additional subsites selected in 1966 consists of five circular 0.04-acre plots and ten 2- by 2-foot quadrats. One sample, designated "lower slope" is simply a replicate of the basic 20-point location. The other two sites are located "mid slope" and "upper slope" in the burn where the preburn tree overstory was less dense and the soils are thinner and rockier.

In addition to these permanent plots describing community development, we have established a series of permanent photographic recording points. At least one shrub of each important species, and several representative views of the overall community have been recorded annually in both black and white and color.

Finally, we were fortunate in locating an old wildfire area only a half mile from the Neal Canyon burn and on a virtually identical topographic site. This area, burned in July 1950, has proved to be a valuable aid in predicting successional development on the Neal Canyon burn.

[1] *Mean area per plant* $= \frac{\Sigma \pi r^2}{4N}$ *where r is the distance to the nearest individual in a quadrant, and N is the number of sampling points.*

Figure 4. — Firing the Neal Canyon area, August 1, 1963.

The Fire

Firing of the Neal Canyon site began just after 8:00 a.m., August 1, 1963, and was completed before 5:00 p.m. the same day. Moisture content of fuel-moisture sticks examined at 3:30 p.m. each day during the week preceding the fire had been a relatively constant 5 to 6 percent. During the firing period, air temperatures rose from the mid-50's to nearly 80° F., and the relative humidity dropped from around 50 percent to 10 percent, or less.[2] Surface winds were mostly under 5 m.p.h. during the day, but fire-induced gusts to 30 m.p.h. were recorded during the peak of burning and estimates of wind velocities within the fire were even higher.

[2] *Data from U. S. Weather Bureau mobile stations at Eagle Creek and on the hilltop above the fire show generally warmer and drier conditions at the hilltop. These figures represent a broad summary from both stations.*

Firelines were burned out first, and then the major fire was started by using a flame thrower on a pickup truck driven once across the middle

Figure 5. — Water-can heat integrating device.

Figure 6.—Representative photograph [illegible] fire, August 1, 1963.

of the site and again across the lower edge. The fire swept into the tree crowns almost immediately; and at progressive intervals the entire area was covered by running flame (fig. 4).

Fire intensity was measured with the water-can integrating devices described by Beaufait (1966). These consist of 1-gallon cans painted flat black and containing 3 liters of water at ambient temperature (fig. 5). The weight of water released as steam through a 1-cm. hole in the can lid is a measure of heat absorbed.

Eighteen pairs of these water-can analogs were placed on mineral soil in six evenly spaced vertical lines within the main 20-acre study area. Rolling rocks and logs destroyed 14 cans, but only four of the 18 pairs were lost. Water loss from the remaining 22 cans ranged from 340 to 1,765 grams, with a mean loss of 939.8 grams. Based on calibrations reported by George (1969) this is equivalent to a mean heat energy flux to the surface of the can of 200 calories per second for about 45 minutes. Similar heat flux values have been recorded in

On site, all the litter and herbaceous material, all dead material less than 3 inches in diameter, and all live stems smaller than 2 inches at the base were completely consumed (fig. 6). Water losses, however, were not clearly related to observed patterns of gross fuel loading (openings, thickets, large shrubs). Apparently, variations in depth of the litter and duff layers were not adequately represented by the occurrence of aerial fuels. Recent studies (Beaufait 1969) have demonstrated that litter and duff shield the can from burning fuels above and that water loss is greatly influenced by the combustion of surface fuels.

Vegetal Succession

Before the Neal Canyon site was burned, the vegetation consisted of 51 plant species, including 6 species of trees and 12 of shrubs. Following the fire, a few species seem to have disappeared, and the relative dominance of important species has been drastically modified. However, one of the interesting modifications shown by the complete listings in the appendix is a substantial increase in number of species during the first 7 years. The tree and shrub component of this forest stand has not changed materially, but the number of species in the herbaceous component has almost doubled. Nevertheless, while the early seral community is considerably richer as to number of species, the mass of biotic production is confined to fewer than a dozen plants. Development of the more important species is summarized in tables 1, 2, 3, and 4.

Patterns of postfire vegetal development in Neal Canyon have been predicated on a hypothetical model of forest succession (fig. 7) in which initial dominance by herbaceous plants is followed with dominance by a shrub community and, in turn, dominance by overstory trees and eventual return to preburn community structure. To date, this model seems adequate even though specific composition of the seral community has demonstrated some very dynamic annual changes.

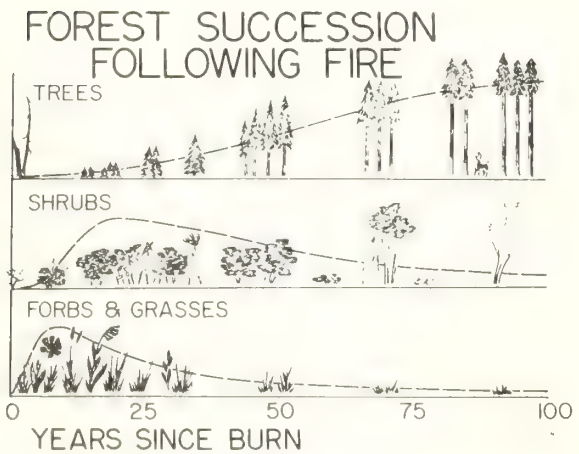

Figure 7. — Hypothetical model of forest succession following fire.

The predicted structure of the community at succession year 20 is suggested by data taken in a 1950 wildlfire area adjacent to the Neal Canyon prescribed burn in 1970 (table 5). There are inherent limitations in this predictive approach because the two burned areas are not exactly alike and because the wildfire area was reforested only by natural seeding. Nevertheless, the similarities between the two sites are so striking that figurative equivalence seems justified in this discussion. The wildfire area is shown in figure 8.

Herbaceous Vegetation

Shortly after the prescribed fire, the new Douglas-fir tree crop was planted and the roads were seeded with a domestic grass mixture. Otherwise, no particular effort was invested in reducing the potential for soil erosion. In this respect, Neal Canyon was a particularly favorable situation because these soils are apparently quite stable even in the absence of vegetal cover. To date, no apparent overland soil movement has been recorded, and the rocks that rolled downhill during the fire probably represent the bulk of surface disturbance on the site.

Nevertheless, it seems significant that herbaceous cover on the Neal Canyon site was almost as dense the first year following the fire as in the preburn community (table 1 and fig. 9). Moreover, while herbaceous cover varied considerably in succeeding years, it never dropped significantly below the preburn level and was, in fact, more than double the preburn percentage in the second year after the fire. This initial surge in herbaceous cover can be almost entirely traced to the development of *Moldavica parviflora*, presumably from residual seed in the duff. One year after the fire, Moldavica was present in 96 percent of the 2-by 2-foot frequency plots and accounted for almost 30 percent of all vegetal cover on the site. When it reached full biennial development in succession year 2, Moldavica covered 37 percent of the total ground surface; and in succession year 3 litter cover jumped to 32 percent due to dead Moldavica stems, leaves, and seed heads.

One obvious question posed by recorded vegetal development concerns the role of Moldavica in shaping successional patterns. The

Table 1. — Percentage cover and frequency of occurrence in 2- by 2-ft. quadrats for abundant herbaceous species and woody species under 18 in. in height, Neal Canyon, 1963-1970

Small-plot data	Pre-burn	Succession year						
		1	2	3	4	5	6	7
	1963	1964	1965	1966	1967	1968	1969	1970
COVER	*Percentage*							
Rock	2	12	6	15	9	10	9	5
Bare ground	4	60	20	21	23	17	15	12
Litter	57	1	5	32	14	17	12	9
Moss and lichen	7	--	--	3	7	12	13	19
Vegetation	30	27	69	29	47	44	51	55
	Frequency of occurrence							
SHRUBS[1]								
Acer glabrum	12	4	x	--	--	--	8	16
Ceanothus velutinus	[2]x	92	92	84	88	92	92	84
Penstemon fruticosus	8	4	24	8	12	16	20	24
Ribes lacustre	20	--	--	--	--	--	--	--
LONG-LIVED PERENNIALS								
Arnica cordifolia	48	24	48	32	36	32	36	40
Aster conspicuus	8	12	20	32	40	40	56	52
Calamagrostis rubescens	24	x	20	28	24	24	24	52
Carex geyeri	52	--	12	20	28	24	24	28
Epilobium angustifolium	20	12	28	48	84	88	88	84
Iliamna rivularis	--	52	36	52	52	56	52	48
Senecio streptanthifolius	44	4	4	4	4	20	32	56
Taraxicum laevigatum	8	x	24	16	40	40	56	68
SHORT-LIVED PERENNIALS								
Cirsium vulgare	12	4	4	16	48	8	36	48
Epilobium watsoni	--	x	48	32	48	12	8	64
Moldavica parviflora	--	96	100	44	100	92	64	76
Phacelia hastata	x	x	20	x	8	4	8	x
ANNUALS								
Bromus tectorum	--	x	4	4	8	4	20	20
Epilobium paniculatum	--	8	88	52	72	20	72	64
Lactuca serriola	--	12	96	32	52	44	20	28

[1] *These data are somewhat misleading because they apply only to seedlings and shrubs under 18 inches in height.*

[2] *"x" indicates species was present in stand but not detected in sample quadrats.*

Table 2. — Density, numbers of plants over 18 in. in height per 1,000 ft.[2]*, Neal Canyon, 1963-1970*

Species	Pre-burn	Succession year						
		1	2	3	4	5	6	7
	1963	1964	1965	1966	1967	1968	1969	1970
Pseudotsuga menziesii	31.4	--	--	T	0.6	0.7	1.2	2.4
Pinus contorta	--	--	--	--	--	T	.2	1.3
Acer glabrum	4.3	1.1	1.1	1.1	1.1	1.5	1.5	1.5
Amelanchier alnifolia	.2	.1	.1	.2	.1	.1	.3	.2
Ceanothus velutinus	.1	--	--	T	.4	11.0	43.4	56.4
Populus tremuloides	--	--	.1	.2	.3	.5	.7	.7
Ribes lacustre	.9	--	--	T	T	--	.3	.1
Ribes viscosissimum	.3	--	--	.8	4.1	9.8	13.3	16.3
Rosa spp.	--	--	--	.1	--	.2	.1	.2
Salix scouleriana[1]	.3	.1	.2	.2	.6	2.4	3.6	4.4
Sambucus racemosa	--	.1	.1	.1	.1	.1	.1	.1
Sorbus scopulina	--	--	--	--	T	T	T	T
Symphoricarpos oreophilus	2.1	--	.3	.6	.7	1.0	1.0	1.1
Other shrubs[2]	--	--	--	.1	.1	.3	.3	.6
Total	39.7	1.4	1.9	3.3	8.2	27.5	66.0	85.3

[1] Salix scouleriana *includes both the 0.14 resprouts per 1,000 feet*[2] *and the seedlings which reached the 18-inch height starting in succession year 3.*

[2] *Includes* Artemisia tridentata, Chrysothamnus nauseosus, Penstemon fruticosa, *and* Shepherdia canadensis.

Table 3. — Estimated total canopy intercept,[1] ft.²/1,000 ft.², Neal Canyon, 1963-1970

Species	Pre-burn	Succession year						
		1	2	3	4	5	6	7
	1963	1964	1965	1966	1967	1968	1969	1970
				Square feet				
Pseudotsuga menziesii	700.0	--	--	--	0.5	0.9	2.2	4.3
Pinus contorta	--	--	--	--	--	T	.1	.8
Acer glabrum	167.1	1.1	13.2	19.4	25.6	33.3	32.9	33.9
Amelanchier alnifolia	2.5	.3	.5	.6	.6	.9	1.2	1.2
Ceanothus velutinus	.2	--	--	.2	1.0	18.3	95.0	99.8
Populus tremuloides	--	--	T	.2	.4	.9	.8	.9
Ribes lacustre	6.7	--	--	T	.1	--	.5	T
Ribes viscosissimum	.6	--	--	.4	4.7	9.7	17.2	15.9
Rosa spp.	--	--	--	.1	--	.2	.1	.2
Salix scouleriana[3]	13.9	2.5	1.1	7.5	12.4	14.6	18.9	21.0
Sambucus racemosa	--	.3	.6	.9	1.4	1.1	.9	.7
Sorbus scopulina	7.0	--	--	--	--	--	.4	.4
Symphoricarpos oreophilus	5.8	--	.1	1.7	3.4	4.8	5.1	3.6
Other shrubs[4]	--	--	--	.1	.1	.6	1.1	2.5
Total	903.8	7.5	19.2	31.1	50.4	85.5	176.4	185.0

[1] *These figures can be divided by 10 to produce percentage canopy cover.*

[2] *This estimate taken from aerial photographs.*

[3] *Including only resprouts before succession year 4. Seedlings represent about one-third of the total in succession year 7.*

[4] *Includes* Artemisia tridentata, Chrysothamnus nauseosus, Penstemon fruticosa, *and* Shepherdia canadensis.

Table 4. — Dominance, basal area (in.^{2}) or aerial crown volume (ft.^{3}), plants over 18 in. in height per 1,000 ft.^{2}, Neal Canyon, 1963-1970

Species	Pre-burn	Succession year						
		1	2	3	4	5	6	7
	1963	1964	1965	1966	1967	1968	1969	1970
	Square inches							
Pseudotsuga menziesii	273.0	--	--	--	--	--	T	T
Pinus contorta	--	--	--	--	--	--	--	--
	Cubic feet							
Acer glabrum	1,376.2	6.6	38.6	72.6	113.4	163.5	170.3	187.4
Amelanchier alnifolia	7.9	.5	.9	1.2	1.7	2.5	3.3	2.9
Ceanothus velutinus	.3	--	--	.3	1.7	28.9	171.1	180.3
Populus tremuloides	--	--	.1	.7	1.4	4.0	3.2	3.8
Ribes lacustre	16.8	--	--	.1	.1	--	1.1	T
Ribes viscosissimum	1.0	--	--	.7	7.8	17.2	33.5	31.3
Rosa spp.	--	--	--	.1	--	.3	.3	.3
Salix scouleriana[1]	254.1	12.0	38.9	67.1	111.8	122.4	156.1	190.3
Sambucus racemosa	--	.6	2.3	3.5	6.4	4.6	4.0	3.3
Sorbus scopulina	60.7	--	--	--	.7	1.3	1.8	1.8
Symphoricarpos oreophilus	11.7	--	.7	2.7	6.2	8.8	9.6	7.8
Other shrubs[2]	--	--	--	.1	.2	.9	2.1	4.3
Total (shrubs only)	1,728.7	19.7	81.6	149.0	251.3	354.4	556.5	613.6

[1] *Including only resprouts before succession year 4. Seedlings represent over one-tenth of the total in succession year 7.*

[2] *Includes* Artemisia tridentata, Chrysothamnus nauseosus, Penstemon fruticosa, *and* Shepherdia canadensis.

Table 5. — Density, canopy area (ft.^{2}) and dominance (basal area in.^{2} or volume ft.^{3}), per 1,000 ft.^{2}, 1950 wildfire adjacent to Neal Canyon burn, succession year 20

Species	Density	Canopy area	Basal area or volume
		Square feet	*Square inches*
OVER 18 INCHES IN HEIGHT			
Pseudotsuga menziesii	7.2	108.1	1.5
Picea engelmannii	1.1	30.8	1.0
Populus trichocarpa	.1	.3	T
			Cubic feet
Acer glabrum	.1	.3	.7
Amelanchier alnifolia	.3	1.8	4.8
Artemisia tridentata	1.0	1.2	2.1
Ceanothus velutinus	49.5	656.0	2,000.9
Chrysothamnus nauseosus	.5	.6	1.5
Populus tremuloides	.9	1.0	2.5
Ribes inerme	.2	.6	1.3
Ribes lacustre	2.6	6.0	12.2
Ribes viscosissimum	14.9	30.5	64.8
Salix scouleriana	6.8	42.5	446.1
Symphoricarpos oreophilus	2.3	9.5	20.3
Total	87.5	750.0	2,559.7
UNDER 18 INCHES IN HEIGHT			
Bare ground	--	10	--
Litter	--	380	--
Moss and lichens	--	50	--
Vegetation, including the following:	--	560	--
	Frequency %		
Agropyron spicatum	52	10	--
Arnica cordifolia	52	30	--
Calamagrostis rubescens	32	130	--
Carex geyeri	68	100	--
Carex rossii	60	--	--
Iliamna rivularis	4	--	--
Epilobium angustifolium	36	20	--
Poa nervosa	80	10	--
Potentilla glandulosa	56	10	--
Senecio streptanthifolius	92	20	--
Taraxicum laevigatum	84	--	--
Viola adunca	68	10	--

Figure 8. — This area is adjacent to Neal Canyon prescribed fire and was burned in a July 1950 wildfire (photographed July 1970). Snowbrush predominates on this site.

species is short lived, and despite continuing high frequency values has not made a significant contribution to live cover since succession year 2. There is no way to judge the effect of Moldavica on the ground level microclimate or on the survival of other plant species; however, data from the upper slope site where Moldavica was not present (table 6) suggest that no particular differences were caused. Throughout the burn, and despite considerable variation in slope and the amount of rock surface, vegetal cover has increased from near 30 percent in succession year 3 to 60 percent in succession year 7. Where Moldavica litter was not present, more bare surface was exposed in succession year 2, but cover of herbaceous plants at succession year 7 is surprisingly consistent over the total burned area.

Even though Moldavica completely dominated the initial development of the Neal Canyon vegetation, there was not much evidence for generalization about other short-lived perennials and annuals in forest succession. Recorded frequencies of similar short-lived plants appear to illustrate fluctuations in seed production rather than significant patterns in plant community development. Some of the herbaceous perennials, on the other hand, do appear to develop within sequences which are logical in terms of species autecology and expected position in the mature plant community.

The most obvious sequence of vegetal development is demonstrated by two pioneering species which were not particularly abundant in the preburn community but increased to dominance in the early seral community. By succession year 3, Moldavica was contributing primarily as litter; *Epilobium angustifolium* and *Iliamna rivularis* had become the most

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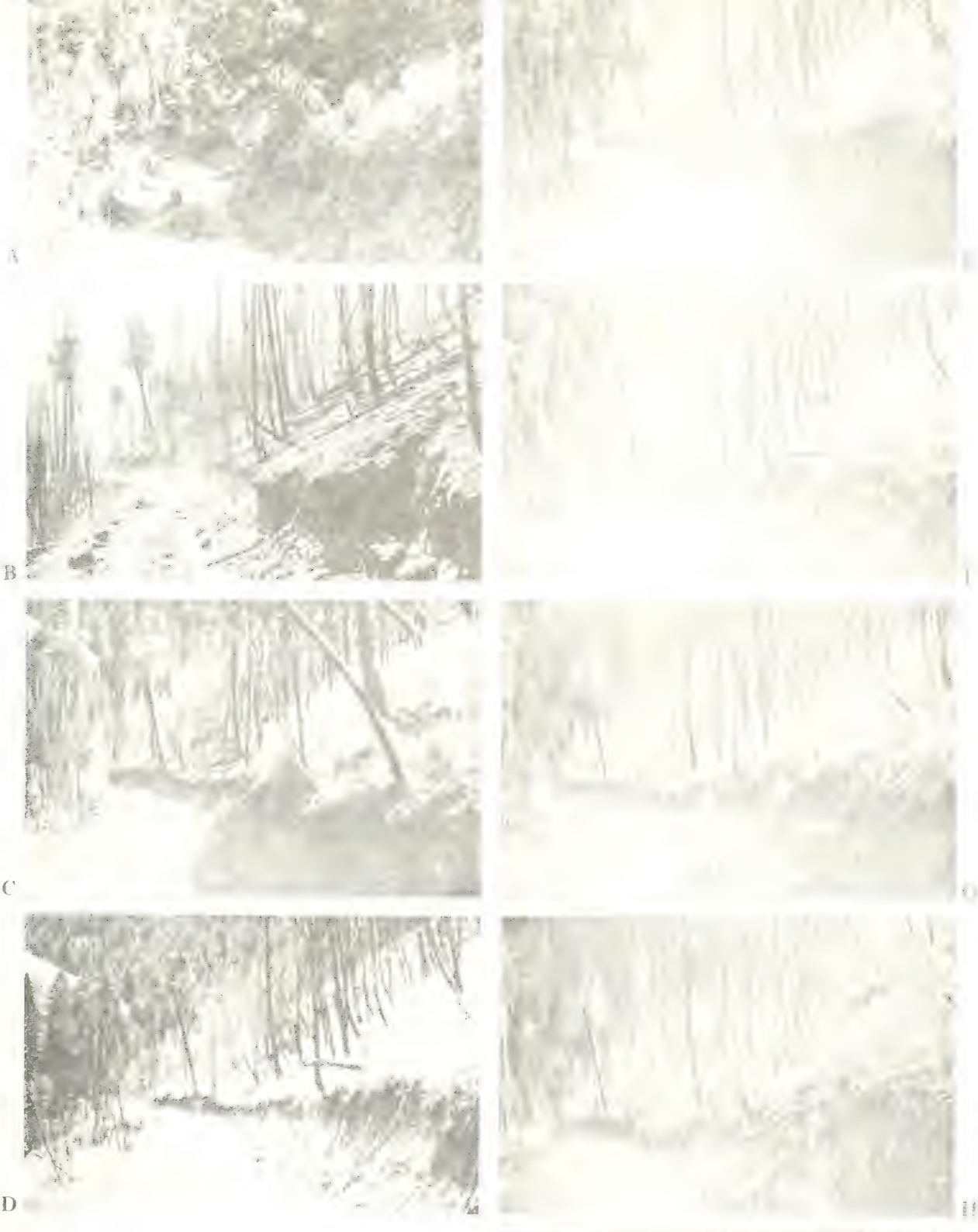


Figure 9. — Prefire (A) and sequential postfire (B through I) vegetation on a representative shrub plot. (A) July 1963; (B) August 1963; (C) July 1964; (D) July 1965; (E) July 1966; (F) July 1967; (G) July 1968; (H) July 1969; (I) July 1970.

Table 6. — Percentage cover of herbaceous species and woody species under 18 in. in height, Neal Canyon subsites, 1966-1970

Area	Succession year				
	3	4	5	6	7
	1966	1967	1968	1969	1970
	Percentage				
UPPER SLOPE:					
Rock	40.0	27.5	37.5	22.5	22.5
Bare ground	30.0	32.5	15.0	22.5	15.0
Litter	2.5	0.0	2.5	12.5	2.5
Moss and lichen	0.0	0.0	0.0	0.0	0.0
Vegetation	27.5	40.0	45.0	42.5	60.0
MID SLOPE:					
Rock	20.0	15.0	12.5	12.5	10.0
Bare ground	20.0	15.0	17.5	15.0	17.5
Litter	30.0	17.5	20.0	10.0	10.0
Moss and lichen	0.0	2.5	2.5	5.0	2.5
Vegetation	30.0	50.0	47.5	57.5	60.0
LOWER SLOPE:					
Rock	5.0	5.0	2.5	2.5	5.0
Bare ground	32.5	20.0	25.0	22.5	12.5
Litter	30.0	22.5	20.0	15.0	15.0
Moss and lichen	2.5	7.5	10.0	12.5	17.5
Vegetation	30.0	45.0	42.5	47.5	50.0

important live plants on the burned area. The two species provided about 40 percent of the vegetal cover and about 20 percent of total cover until sucession year 6 when *Ceanothus velutinus* became the dominant species. Predictions for future development suggest that both herbaceous species have already reached a peak and will decrease by succession year 20 (table 5) to frequencies very near those recorded in the preburn community.

Another developmental sequence describes the recovery of some rhizomatous species which were relatively important in the preburn community. Both *Arnica cordifolia* and *Calamagrostis rubescens* appeared in the early seral stand at frequencies only slightly different from those recorded before the fire. Field notes on individual species confirm substantial aggregation rather than random distribution. Frequency data from the 1950 wildfire (table 5) suggest that no major expansion of these species will be recorded although both will probably provide increased cover values as aggregates fill in and then decline somewhat as the shrub stand reaches maturity.

A third sequence of development describes the reestablishment of non-rhizomatous species from the preburn community. *Carex geyeri* and *Senecio streptanthifolius* appeared in the early seral community at frequencies far below preburn levels. During the first 7 years, both species have increased at rates which seem slow but are consistent with the high frequencies expected by succession year 20. In both species, this peak should be followed by a slow decline to the plateau indicated by preburn frequencies.

Despite recorded vegetal resurgence on this burned site, the potential for soil loss created by burning should not be minimized. Before the fire, litter cover was present on over half the soil surface and bryophytes protected another 7 percent. Moreover, overhead canopy in the various tree and shrub layers (table 3) probably approached 100 percent.

By contrast, litter, bryophytes, and tree canopy were all missing in succession year 1, and shrub canopy totaled less than 1 percent. Nearly three-fourths of the surface had no protection until the biennial growth of Moldavica peaked in succession year 2. On a less stable soil, this might have created a significant erosion problem. However, the percentage of surface without vegetal cover (rock and bare ground), has been dropping steadily through succession years 4, 5, 6, and 7 at about 3 to 5 percent each year — a rate consistent with the 1 percent bare ground expected for succession year 20 (table 5).

Woody Vegetation

Prior to burning, the woody plant community in Neal Canyon was dominated by the Douglas-fir overstory. A few large stumps indicated that trees up to 36 inches in diameter had once grown on the site. These very large stems had been removed in two selective timber sales between 1950 and 1960; but there was no evidence either in the form of burned snags or charred material (on the ground) to indicate that the stand had been otherwise disturbed for at least a century. Increment cores from some of the dominant Douglas-firs revealed ages ranging from 28 to 170 years and a cross-section from the largest available willow stem showed 34 annual growth rings.

With the exception of standing snags, this overstory was completely removed by fire, but very few of the woody plants other than trees were actually killed. Most of the shrubs on the site resprouted; but in terms of total vegetal canopy, the woody plants in Neal Canyon contributed much less cover than the herbaceous plants during early succession. However, the projection to succession year 20 (table 5) and the expected return of the preburn mature forest (table 2), both demonstrate the long-term significance of the woody overstory. Moreover, these plants are of particular interest because they provide wildlife habitat values and also represent the eventual timber crop.

Trees: In the first year after the fire, new trees were established on the burned site by three different methods. In one part of the burn, the Ketchum Ranger District planted Douglas-fir stock from the Forest Service Nursery at Savenac, Montana. This stock has done exceptionally well, and by the sixth growing season was well established and healthy (fig. 10). In other parts of the burn, Douglas-fir was direct seeded, and there has been some natural seeding of both Douglas-fir and lodgepole pine.

Figure 10. — Seventh year Douglas-fir in Neal Canyon plantation.

On the main Neal Canyon study site, the first five 0.04-acre plots extend through a plantation in which 45 Douglas-firs over 18 inches high were recorded. In addition, these 5 plots contain 24 lodgepole pines. The remaining 15 plots, and the additional 15 subsite plots, contain 58 more Douglas-firs and 19 lodgepole pines. Finally, 7 Douglas-fir seedlings and a whitebark pine *(Pinus albicaulis)* were recorded in the 2- by 2-foot plots. These data are obviously inadequate to establish survival and stocking rates for the Neal Canyon burned area, but the indicated density for trees is certainly higher than the density recorded in the 20-year stand. Depending on seedling survival and further interseeding, the probable tree density can be estimated at somewhere between 9 and 27 stems per thousand square feet (400-1,200 stems per acre).

Prediction of the date of crown closure is, of course, purely conjectural on the basis of the inadequate sample available at this time. However, projection of the crown-width on stem diameter regression presented by Smith, Ker, and Csizmazia (1961) shows that 1,200 Douglas-fir, evenly spaced, would reach canopy closure at a d.b.h. of 1 inch. Slightly over 400 per acre, evenly spaced, would reach canopy closure at 4 inches d.b.h. Presuming moderately good growing conditions, Douglas-fir on the Neal Canyon site could reach a d.b.h. of 4 inches in about the thirtieth year of succession.

Shrubs: As of succession year 4, total numbers of shrubs over 18 inches tall were about the same as recorded before the fire. However, by succession year 7, shrub density had increased tenfold. Canopy intercept, on the other hand, had not reached the preburn level and crown volume in succession year 7 was just over one-third of the preburn volume. Projection of shrub canopy to succession year 20, as suggested by table 5, indicates a continuing in-

crease with shrub canopy equaling the herbaceous cover percentage sometime between succession years 10 and 15.

Within the shrub community, there were some substantial shifts in dominance among various species. In the preburn community, mountain maple accounted for more than half of shrub density, over 80 percent of the shrub intercept and nearly 80 percent of the shrub crown volume. During the first 2 years of succession, comparative densities remained fairly close to 10 maples for each Scouler willow *(Salix scouleriana)*, but because willow resprouted so much more vigorously, canopy intercept of maple was only slightly greater and crown volume of willow was greater than that for maple.

In succession year 3, total volumes of both species were about equal; and by succession year 5, maple was again the dominant shrub species. However, in succession year 6, crown volume of snowbrush reached about the same level as maple and willow; and straight-line projections to estimates for succession year 20 (table 5) suggest that the volume of snowbrush will exceed the combined volumes of all other shrubs after succession year 9. This dominance will very likely be maintained through most of the next 30 to 50 years or until the developing trees overtop and shade the snowbrush.

Changes among other shrub species are somewhat less spectacular, but the effects of fire are certainly evident in several ways. The two Ribes species, for example, have reversed relative importance as a result of the fire. Sticky currant was infrequent in the preburn community, but following the fire, many new plants have appeared and the species has made a substantial contribution to shrub canopy and volume since about succession year 4. Projection to succession year 20 suggests continuing importance for a number of years.

Meanwhile, prickly currant has virtually disappeared from the main site of investigation. The only plants recorded constitute such a small sample that the species has no apparent role in community structure. Data from other sites within the burn (table 7) show that this is not just a peculiarity of the one site. In every area sampled, *R. viscosissimum* is substantially more dense than *R. lacustre*. Projections to succession year 20 suggest a slow increase requiring as much as 30 to 40 years to regain preburn crown volumes.

Shrub Growth Rates: Although the shrub contribution to total vegetal cover is not expected to equal the herbaceous contribution until succession year 10, the management significance of these woody plants is relatively high. Forage and cover for game animals are produced by many shrub species, and one of the significant questions of habitat manipulation concerns the speed at which shrub recovery takes place. One expression of growth is supplied by the community-structure summary (tables 2-4). However, these summary data do not provide an unbiased expression of growth rates because they include both the increases in plant size and apparent increases in density as smaller plants surpass the artificial 18-inch height limit of our sampling method. Also, when cover values or forage values are considered, the average size of all plants is probably somewhat less important than the average for those larger plants which will protrude through the snow and, presumably, be the longest lived in any eventual competition for light and moisture.

Accordingly, samples including 4 to 31 plants of 6 species which contribute over 95 percent of shrub volume have been selected for an individual growth-rate study. These samples include those plants of each species first to exceed the sampling height limit of 18 inches. They are not marked on the study site as individual plants, but no more than six of any one species are included in a single 0.04-acre plot and it is generally possible to identify these larger specimens on a year-to-year basis in the data.

Because these samples are quite small, crown volume and height means presented in table 8 must be interpreted with discretion. Data on snowberry, for example, show a 1970 mean size of 19.0 $ft.^3$, but this represents a range from 6.9 $ft.^3$ for nine plants on the main study site to 25.8 $ft.^3$ for 15 plants on the upper slope. Despite the small samples, however, it is possible to make some general comparisons among the resprouting and growth rates of the six species listed.

Tall shrubs. — Plants that resprout on a

Table 7. — Density and aerial crown volume for species over 18 in. in height and more than one ft.^{3} per 1,000 ft.^{2}, Neal Canyon subsites, 1966-1970

Area	1966	1967	1968	1969	1970	1966	1967	1968	1969	1970
	Number of plants					Crown volume ft.^{3}				
UPPER SLOPE:										
Acer glabrum	0.9	0.6	1.5	1.4	1.3	26.1	38.6	90.0	104.5	77.3
Artemisia tridentata	--	.1	--	.1	.2	--	.1	--	.2	1.1
Ribes lacustre	.1	.5	.2	.2	.5	.7	2.0	1.4	1.8	2.5
Ribes viscosissimum	.1	--	.7	.8	2.4	.1	--	.7	1.4	5.8
Symphoricarpos oreophilus	9.4	9.3	11.2	10.9	10.3	79.0	104.3	132.3	136.1	125.0
Totals	10.5	10.5	13.6	13.4	14.7	105.9	145.0	224.4	244.0	211.7
MID SLOPE:										
Acer glabrum	.2	.2	.3	.3	.3	.3	1.8	4.2	5.9	10.4
Amelanchier alnifolia	.2	.3	.9	.8	.6	3.1	10.2	14.9	13.3	21.0
Ceanothus velutinus	--	.1	1.5	8.0	11.1	--	.1	5.0	33.9	46.9
Ribes viscosissimum	.1	.2	.8	1.0	2.5	.1	.7	1.9	3.7	6.5
Rosa spp.	.3	.1	.2	.1	.1	.3	.5	.8	1.0	.4
Symphoricarpos oreophilus	1.5	1.8	3.7	3.3	2.6	9.6	16.2	28.8	30.8	27.2
Totals	2.3	2.7	7.4	13.5	17.2	13.4	29.5	55.6	88.6	112.4
LOWER SLOPE:										
Acer glabrum	.1	.1	.1	.1	.1	2.0	3.8	3.8	3.8	4.1
Amelanchier alnifolia	.3	.3	.5	.5	.5	3.7	1.5	4.9	6.3	4.8
Artemisia tridentata	--	.1	.1	.3	.1	--	.4	.5	1.2	.3
Ceanothus velutinus	--	--	13.3	21.8	33.4	--	--	45.7	96.4	125.0
Populus tremuloides	.2	.2	1.0	.6	1.1	.2	.3	1.5	2.0	--
Ribes lacustre	.2	.2	1.0	1.3	1.8	.2	.4	2.6	7.4	4.4
Ribes viscosissimum	4.9	8.4	21.9	21.3	28.1	4.5	21.6	51.0	61.6	72.5
Salix scouleriana	1.4	1.5	3.3	4.4	5.9	189.9	200.7	253.8	609.2	721.4
Sorbus scopulina	--	.1	.2	.1	--	--	.5	1.0	2.0	--
Symphoricarpos oreophilus	.3	.2	.3	.2	.5	1.6	1.4	1.8	2.0	2.9
Totals	7.4	11.1	41.7	50.6	71.5	202.1	230.6	366.6	791.9	935.4

Table 8. — Average height and volume ($ft.^3$) for a selected sample of shrubs, Neal Canyon, 1963-1970

Species	Sample size	Succession year						
		1	2	3	4	5	6	7
		1964	1965	1966	1967	1968	1969	1970
		Average height (ft.)						
Salix scouleriana	6	5.1	8.0	8.3	8.5	8.8	9.7	10.5
Acer glabrum	17	1.8	3.0	3.6	4.4	5.0	5.4	5.8
Symphoricarpos oreophilus	31	--	--	1.7	1.9	1.9	2.1	1.9
Ceanothus velutinus	14	--	--	--	1.5	1.9	2.2	2.4
Ribes lacustre	4	--	--	1.7	1.6	1.5	2.4	1.9
Ribes viscosissimum	26	--	--	1.6	2.0	2.0	2.5	2.5
		Average volume ($ft.^3$)						
Salix scouleriana	6	82.7	231.6	462.1	760.1	812.5	978.9	991.8
Acer glabrum	17	5.8	46.0	75.3	126.3	157.3	173.3	202.1
Symphoricarpos oreophilus	31	--	--	11.9	16.6	20.1	23.1	19.0
Ceanothus velutinus	14	--	--	--	2.7	6.9	15.5	19.3
Ribes lacustre	4	--	--	2.6	3.1	4.4	11.5	6.2
Ribes viscosissimum	26	--	--	1.4	4.4	5.7	8.5	7.2

Table 9. — Decline in number of snowbrush plants, 1964-1970, Neal Canyon prescribed burn area per 1,000 $ft.^2$

	Succession year						
	1	2	3	4	5	6	7
	1964	1965	1966	1967	1968	1969	1970
Seedlings (<18 in. tall)	4,460	2,610	2,130	1,750	1,490	1,160	740
Plants (>18 in. tall)	--	--	T	0.4	11.0	43.4	56.4
Total *Ceanothus velutinus*	4,460	2,610	2,130	1,750.4	1,501.0	1,203.4	796.4

burned-over site provide two values for wildlife. The first, and most obvious, is production of forage at a height within reach of animals. To some degree, however, the use of this forage may be limited by the lack of natural escape cover. Thus, a shrub that furnishes both food and cover could be somewhat more valuable than one which furnishes only forage.

Among the species present on the Neal Canyon site, only the willow and mountain maple seem likely to be dense enough and tall enough to provide cover for big game animals before the trees fulfill this role. Adequate cover for grouse and small mammals is probably supplied

(1 year)

(3 years)

(7 years)

Figure 11. — Resprouting Scouler willow (S. scouleriana), *1, 3, and 7 years after the Neal Canyon prescribed fire.*

(1 year)

(3 years)

(7 years)

Figure 12. — Resprouting mountain maple (A. glabrum), *1, 3, and 7 years after the Neal Canyon prescribed fire.*

by all the woody species and some of the herbaceous plants. For small animals, however, density of cover is probably more significant than height.

Measurements of resprouting and growth of willow in Neal Canyon provide a most convincing demonstration of plant recovery following crown-kill by fire (fig. 11). Resprouting willows were over 5 feet tall in the first year and the average plant volume equaled the preburn average by the fourth growing season. However, nearly 80 percent of the height growth for 7 years was achieved in the first two growing seasons, and continuing expansion has been along horizontal planes.

Considering the recorded rate of height growth, willow was at least partially out of reach for game animals by the second growing season. However, it appears that prefire willow heights ranging up to 27 feet will not be achieved until these plants are forced into competition with overstory trees.

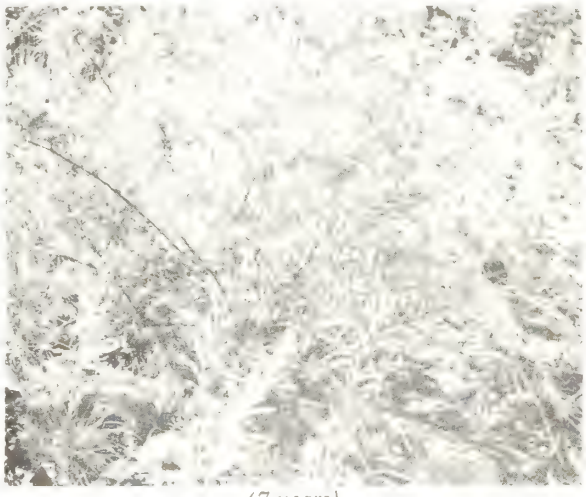
Growth patterns of mountain maple were much different than those of willow (table 8 and fig. 12). Height growth in the first 2 years only produced 52 percent of the 7 year height and both the height and volume increments have been relatively constant from year-to-year throughout the study. The maple, obviously, did not contribute much to cover requirements of big game on this site until possibly the third year of regrowth. On the other hand, forage produced has yet to grow completely out of reach and it is apparent that maple can make a substantial contribution to forage balance on a range which has enough willow to provide adequate cover.

Low shrubs. — The low shrub specimens listed in table 8 probably represent both seedlings and resprouts. Densities of sticky currant and snowbrush in particular, have increased substantially above preburn densities in the 7 years since the fire. It is also of interest that all species except prickly currant are represented by plants substantially larger than the mature plants of the preburn community. Snowberry, for example, has an average canopy area of 10 ft.^{2} for these larger plants as compared to less than 3 ft.^{2} for mature plants in 1963 (fig. 13).

All species except snowbrush showed a drop in height and volume from 1969 to 1970. This

(1 year)

(3 years)



(7 years)

Figure 13. — Resprouting snowberry (S. oreophilus), *1, 3, and 7 years after the Neal Canyon prescribed fire.*

is interpreted as the effect of heavy winter snow, but it also suggests that sticky currant and snowberry may have reached the potential in size development which can be expected on this site. When the overstory of trees finally provides some protection from snow, shade is expected to cause a reduction in average size to preburn levels for these two species. In the case of prickly currant, however, optimum environmental conditions will not occur until overstory trees produce shade. Thus, snow is expected to be somewhat limiting during the treeless period, but as soon as site conditions are adequately modified this species should respond vigorously.

From the wildlife standpoint, snowberry and the two currants are relatively unimportant in this stand. All are moderately palatable to big game and the currants may supply some fruit for smaller animals, but in the presence of the existing variety of highly palatable shrubs, the forage contribution of these species will be small.

Snowbrush, on the other hand, is generally considered to have high palatability, and when available in the amounts present on this site must be considered a significant forage resource. Moreover, it is a forage resource directly resulting from the use of fire as a management tool. Gratkowski (1962) has shown that snowbrush seeds can lie in the duff of a mature timber stand for periods ranging up to 300 years. Then, following fire in the forest and a period of cold stratification, dormancy is broken and the accumulated seed production of 30 to 50 years germinates on the burned area.

In the Neal Canyon study, our samples for 1964 showed more than 4,000 snowbrush seedlings per 1,000 ft.^{2} of surface (nearly 200,000 per acre). Over 40 percent of these plants had died by succession year 2, and in succession year 7 less than one fifth of the original plants were still alive (table 9). Of these, only 7 percent are over 18 inches in height (fig. 14), and yet, they contribute over 50 percent of the shrub cover (table 3). Based on the prediction to succession year 20 (table 5), snowbrush density will eventually be reduced to about 50 plants per 1,000 ft.^{2} with a canopy area approaching 70 percent.

(1 year)

(3 years)

(7 years)

Figure 14. — Snowbrush (C. velutinus) *seedlings at 1 year and representative plants 3 and 7 years after the Neal Canyon prescribed fire.*

Prescribed fire has advantages in certain situations and limitations in others. One of the major limitations is that potential results of prescribed fires are not well understood and the disadvantages can easily be overemphasized. Data obtained from the prescribed burn in Neal Canyon will not resolve the problems of fire management, but this burn does demonstrate that there are situations in which virtually all of the results can be considered favorable.

The Neal Canyon prescribed fire was conducted in August under extreme conditions. Yet, the recorded heat flux was within ranges obtained in slash disposal fires on logged sites in the northern Rocky Mountains and the fire was not lethal to any significant proportion of the plant species that had resprouting capabilities. The heat flux to soil surface and vegetation obtained in the Neal Canyon prescribed fire can be duplicated following logging in situations similar to the one recorded here. However, Shearer and Hammer[4] have found that soil moisture is generally higher and heat penetration less under slash than in adjacent undisturbed forest stands. Until these factors are fully evaluated, duplication of the biological results obtained in Neal Canyon may be limited to similar ecological situations in standing timber.

The postfire resurgence of both herbaceous and shrub cover indicate the potential value of prescribed fire in managing vegetation for the benefit of wildlife. The preburn forest community on the Neal Canyon site contributed very little forage for big game. Within 1 year after burning, resprouts of tall shrubs had become available to animals, and the initial development of a substantial browse field was evident in the germinating snowbrush. Finally, although the study was not specifically designed to evaluate silvicultural success or soil movement and watershed effects, both the planted and direct-seeded trees appear adequate and there is no evidence that burning caused watershed damage.

Prediction of Results

One of the most noteworthy ecological comparisons in the Neal Canyon study is the relative similarity of preburn and postburn forest communities. New plant species did appear following the fire, particularly in the herbaceous category. However, the major constituents of the postburn community were represented in the preburn forest stand. Because they were so represented, it is reasonable to assume that appropriate preburn sampling can be used to predict postfire cover patterns for forest communities other than the one described here.

An example of the form such predictions might take is illustrated in figure 15. Following the hypothetical model of figure 7, data from the preburn sample and the first 7 postfire years (tables 1 and 4) are shown as actually recorded. Data from the 20-year-old burn (table 5) were extremely helpful but not absolutely necessary as a guideline in determining the probable course of various curves. Beyond 20 years, all curves have been smoothed to expected values near the preburn level in about

[4] *Raymond C. Shearer and Robert G. Hammer. Soil moisture, soil temperature and root mortality associated with prescribed burning on western larch forests. Intermountain Forest and Range Exp. Station, Ogden, Utah. (Manuscript in preparation)*

the fiftieth year. Development rate curves are already available for many tree species but much more work is needed to verify the reactions and development rates of shrubs and herbaceous cover on other sites. However, even the limited information available in a pretreatment sample would provide an empirical base for estimating shrub curves.

If the model of figure 15 were combined with similar models for other sites, long-term patterns of both forage and cover availability could be predicted for areas as large as herd-management units or Ranger Districts. Such predictions would be of significant value in integrating wildlife management with other resource management disciplines. Toward this objective, a computer program designed to integrate winter-range forage production estimates on large areas has already been developed by Region 1 of the U. S. Forest Service (Giles and Snyder 1970). Further refinements will be required to incorporate summer ranges and cover values, but the potential for improving current habitat management practices and stabilizing big game herd levels appears to be substantial.

In the present state of the art, the Neal Canyon prescribed burn may be most useful in supplying a specific logic for the manipulation of vegetation on small areas for the benefit of wildlife. Where preliminary sampling indicates a potential for the development of a big game forage resource with fire or logging, the predicted composition of the postburn community can be used as a guideline in determining the size of the desired opening and the requirements for juxtaposition of other vegetal types. Figure 15, for example, shows a substantial forage resource within 2 years after the Neal Canyon burn; but the cover within the burned area was relatively poor until the mountain maple began to reach a height of 4 to 5 feet. On some sites, the absence of tall shrub species might prolong the cover-free period 10 to 15 years until trees reach a height which will encourage access for animals. This could be particularly important on a white-tailed deer range and would logically lead to the creation of smaller openings or the provision of uncut stringers of trees to encourage utilization of the newly created forage resource.

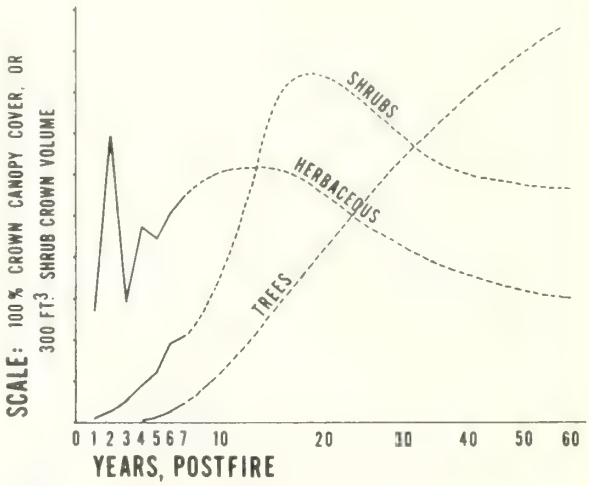

SCALE: 100% CROWN CANOPY COVER, OR
300 FT³ SHRUB CROWN VOLUME
SHRUBS
HERBACEOUS
TREES
0 1 2 3 4 5 6 7 10 20 30 40 50 60
YEARS, POSTFIRE

Figure 15. — Theoretical development of Neal Canyon vegetal community.

Conclusions

In summary, the prescribed fire on the Neal Canyon site can be considered an exceptional success in virtually every respect. Timber management objectives were achieved, wildlife habitat was markedly improved, and watershed protection was not compromised. Moreover, the fire provides a basis for predictions of the effects of similar fires on other sites. However, it cannot be too strongly emphasized that fire can also produce vastly different results in other ecological situations. Areas with depauperate vegetal communities and fragile soils do not recover from burning in the relatively short time periods suggested at Neal Canyon. Some areas, in fact, may never recover if subjected to repeated fire as a treatment practice. Fire can be useful as a management tool only when we can predict and fully understand the results it will produce in specific locations. The Neal Canyon fire provides one step toward this understanding.

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APPENDIX

PLANT SPECIES PRESENT ON NEAL CANYON PRESCRIBED FIRE SITE, 1963-1970[1]

(Nomenclature follows Hitchcock et al., 1955-1969[2])

Species	Pre-burn	Succession years						
		1	2	3	4	5	6	7
	1963	1964	1965	1966	1967	1968	1969	1970
TREES								
Abies lasiocarpa	x	--	--	--	--	--	--	--
Picea engelmannii	x	--	--	--	--	--	--	--
Pinus albicaulis	x	--	--	--	--	--	--	x
Pinus contorta	x	--	--	4	4	4	4	x
Populus tremuloides	x	--	x	x	x	x	x	x
Pseudotsuga menziesii	20	20	4	16	16	16	16	24
SHRUBS								
Acer glabrum	12	4	x	x	x	x	8	8
Amelanchier alnifolia	x	x	x	x	x	x	x	x
Artemisia tridentata	x	x	--	--	x	x	x	x
Ceanothus velutinus	x	92	92	84	88	96	92	84
Chrysothamnus nauseosus	--	x	--	x	x	x	4	x
Chrysothamnus viscidiflorus	--	--	--	--	--	x	x	x
Cornus stolonifera	x	--	--	--	--	--	--	--
Haplopappus macronema[3]	--	--	--	--	--	x	--	--
Penstemon fruticosus	8	4	24	8	12	16	20	24
Ribes lacustre	20	--	x	x	x	x	x	4
Ribes viscosissimum	4	24	44	20	28	24	20	20
Rosa woodsii[3]	--	--	--	x	--	x	x	x
Salix scouleriana[3]	x	x	x	x	x	x	x	x
Sambucus racemosa	x	x	x	x	x	x	x	x
Shepherdia canadensis	--	--	--	x	x	x	x	x
Sorbus scopulina	x	--	--	x	x	x	x	x
Symphoricarpos oreophilus	12	x	x	x	x	4	4	4
HERBACEOUS AND LOW WOODY PERENNIALS								
Achillea millefolium	--	--	--	x	x	x	x	8
*Agropyron cristatum**	--	--	--	x	x	x	x	x
Agropyron spicatum	8	--	--	4	4	8	12	16
*Agropyron trichophorum**	--	--	--	--	--	--	--	4
Antennaria rosea	x	--	--	--	--	x	4	8
Arnica cordifolia	48	24	48	32	36	32	36	40
Aster campestris[3]	--	--	--	--	--	--	x	x

(continued)

Species	Pre-burn	Succession years						
		1	2	3	4	5	6	7
	1963	1964	1965	1966	1967	1968	1969	1970
Aster conspicuus	8	12	20	32	40	40	56	52
Aster foliaceus	--	--	--	--	x	4	4	8
Berberis repens	x	4	--	--	--	--	--	--
*Bromus inermis**	--	--	--	12	8	12	24	16
Calamagrostis rubescens	24	x	20	28	24	24	64	52
Carex geyeri	52	12	12	20	28	24	24	20
Carex rossii	--	--	12	28	28	28	28	36
Castilleja miniata	8	--	--	--	--	x	x	4
Cirsium arvense[4]	--	--	--	--	--	x	x	x
Clematis columbiana	4	x	x	--	--	x	x	x
Epilobium angustifolium	20	12	28	48	84	88	88	84
Galium triflorum[3]	x	--	--	--	--	--	--	--
Heuchera parviflora[3]	x	--	--	--	--	--	--	--
*Hordeum jubatum**	--	--	--	--	--	--	x	--
Iliamna rivularis	--	52	36	52	52	56	52	48
Lithospermum ruderale	x	--	x	--	--	--	--	x
*Lolium multiflorum**	--	--	--	x	--	--	--	--
Lomatium triternatum	--	--	--	--	--	--	x	--
Melica bulbosa[3]	--	--	--	x	--	--	--	--
Osmorhiza chilensis[3]	x	--	--	--	--	--	--	x
Penstemon attenuatus	--	--	--	--	--	--	--	x
Poa nervosa	20	--	--	x	x	4	4	16
Potentilla arguta[4]	20	--	x	--	x	x	16	8
Potentilla gracilis	x	--	--	--	--	--	--	--
Pyrola secunda	12	--	--	8	12	8	8	4
Pyrola virens	x	--	--	--	--	--	--	--
Senecio serra	--	--	--	x	--	4	8	x
Senecio streptanthifolius	44	4	4	4	4	20	32	56
Sitanion hystrix	--	--	--	--	--	--	--	4
Smilacina racemosa	x	x	4	--	--	--	--	--
Taraxacum laevigatum[5] *	8	4	24	16	40	40	56	68
Trisetum spicatum	12	--	--	x	--	--	--	x
Valeriana acutiloba[3]	x	--	--	--	--	--	--	x
Viola adunca	12	8	12	--	--	x	x	8
BIENNIALS AND SHORT-LIVED PERENNIALS								
Arabis drummondii[6]	x	--	x	x	x	x	x	4
Arabis holboellii	4	--	--	x	12	8	24	20
Chaenactis douglasii[3]	--	--	--	--	--	--	x	x
Cirsium canovirens	--	--	--	--	--	x	x	8
*Cirsium vulgare**	12	4	4	16	48	40	36	48

(continued)

Species	Pre-burn	Succession years						
		1	2	3	4	5	6	7
	1963	1964	1965	1966	1967	1968	1969	1970
Corydalis aurea	--	4	4	--	--	--	--	--
Epilobium watsonii	--	x	48	32	48	12	8	56
Erigeron acris	--	--	--	--	--	4	4	4
Frasera speciosa	16	--	4	--	--	x	x	x
Machaeranthera canescens	--	--	--	--	--	x	x	8
Moldavica parviflora	--	96	100	44	100	92	64	76
Phacelia hastata	x	8	20	x	8	4	8	x
*Potentilla biennis**	--	--	--	--	--	--	--	x
*Tragopogon dubius**	--	x	24	8	24	40	36	28
*Verbascum thapsus**	--	--	4	--	--	16	20	28
ANNUALS								
*Bromus tectorum**	--	4	4	4	8	4	20	20
*Capsella bursa-pastoris**	--	x	x	--	4	--	--	4
*Chenopodium album**	--	--	--	x	4	x	x	x
Collinsia parviflora	8	x	8	4	12	8	20	12
Collomia grandiflora	--	--	--	4	12	8	16	16
*Conzya canadensis**	--	x	--	--	--	--	--	--
Cryptantha affinis	4	x	4	x	8	20	8	12
Descurainia richardsonii	x	x	x	--	--	x	4	4
Epilobium paniculatum	--	8	88	52	72	80	72	64
Galium aparine	--	--	--	--	--	--	--	x
Gayophytum nuttallii	--	--	--	x	4	x	x	4
Geranium bicknellii[3]	--	x	--	--	--	--	--	--
*Lactuca serriola**	--	12	96	32	52	44	20	28
Lepidium virginicum	--	--	--	--	--	x	x	--
Madia glomerata	--	--	--	--	--	--	--	x
*Myosotis micrantha**	--	--	--	--	--	--	--	4
Polygonum douglasii	--	--	--	--	x	x	4	x
*Sisymbrium altissimum**	--	--	--	--	--	--	--	x
*Spergularia rubra**	--	--	4	--	--	--	--	--
*Triticum aestivum**	--	x	8	--	--	--	--	--

[1] *"x" indicates species was present in stand but not detected in sample quadrats. Numerical designations are percentage frequency of occurrence in twenty-five 2- by 2-foot quadrats.*

[2] *C. Leo Hitchcock, Arthur Cronquist, Marion Ownbey, and J. W. Thompson, Vascular Plants of the Pacific Northwest. Seattle: Univ. Wash. Press (5 parts, 2,978 p.) 1955-1969.*

[3] *Tentative identification pending collection of flowering material.*

[4] *Includes* P. glandulosa.

[5] *May include* T. officinale.

[6] *May include* A. glabra.

**Introduced species.*

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

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MATCHACURVE - 2 FOR ALGEBRAIC TRANSFORMS TO DESCRIBE CURVES OF THE CLASS X^n

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ABSTRACT

Graphed curves of the class, X^n, can be quickly scaled to and compared with the wide array of standard curves presented. If a standard can be found that suitably matches the scaled curve, the algebraic transform specified for the standard can be applied to the X values of a relevant data set and these can be scaled to their corresponding Y values by least squares to arrive at the fitted model.

INTRODUCTION

The analyst often initiates a two-dimensional regression analysis by hand-fitting the expected curve for an XY relation through a set of plotted data points called the "graphed curve" in this paper.

Assume he wants next to find a mathematical form of the independent variable, X, which when scaled to the graph emulates the graphed curve with acceptable accuracy. If the curve is linear, X itself is, of course, the appropriate form. But if the curve is nonlinear, a matching nonlinear form of X should be the object of his search. Once having found a suitable form, the analyst can rescale it to the actual data points of any relevant data set[1/] by least squares, and the development of the estimating equation is complete.

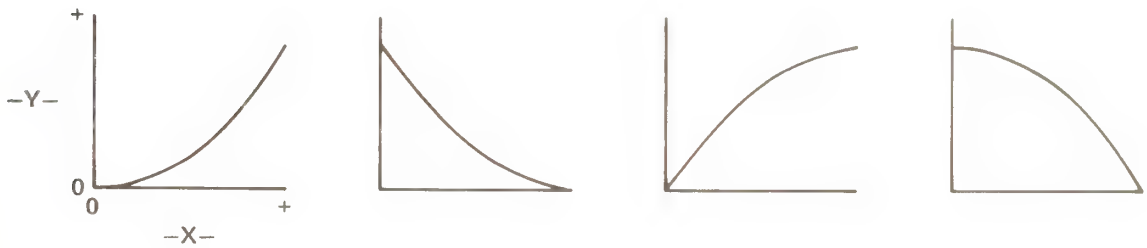
In this paper we have attempted to reduce the effort required to find acceptable transforms of the X^n class. The analyst simply compares a scaled version of his graphed curve to graphed Standards (page 9) and selects the two adjacent ones most nearly like his own in shape, a process hereinafter referred to as "Matchacurve."

Interpolation between the transforms given for these Standards results in identification of the best alternative offered by the system. It is this transform of X that is finally fitted to a relevant data set by least squares.

Three unique sets of standard curves are presented. Each set is based on a selected array of n in X^n, with limits as shown:

Set	*n-array limits*
1	$1.00 \leq n \leq 20.00$
2	$0.10 \leq n \leq 1.00$
3	$-2.00 \leq n \leq -0.01$

Each set of Standards is transformed as required (see Appendix C) to appear in each of the four basic positions in which the analyst's curve can occur in the upper right quadrant so that there are 12 sets of Standards in all--3 sets in each of 4 positions.



[1/] Either the data set from which the graphed curve is derived or some other set to which this curve is judged applicable.

The scaling procedure for sets 1 and 2 is shown in the example that follows. Set 3, because it involves reciprocals and because the latter are indeterminant at X = 0, requires that Y_p be determined within a slightly abbreviated X-range as explained in the last paragraph under the section labeled "An Example."

For the sake of efficiency, then, it is suggested that the analyst's curve be scaled first for comparison to sets 1 and 2[2/] ; the curve will be scaled for comparison to set 3 only when no suitably similar form can be found in sets 1 and 2.

Where the analyst's curve lies either partly or wholly in some quadrant other than "upper right" (i.e., not oriented as the curves above), adjust either the X- or Y-scale, or both, to put the curve on the same basis as the standards before applying Matchacurve --see Appendix A.

AN EXAMPLE

This example applies as shown to sets 1 and 2.

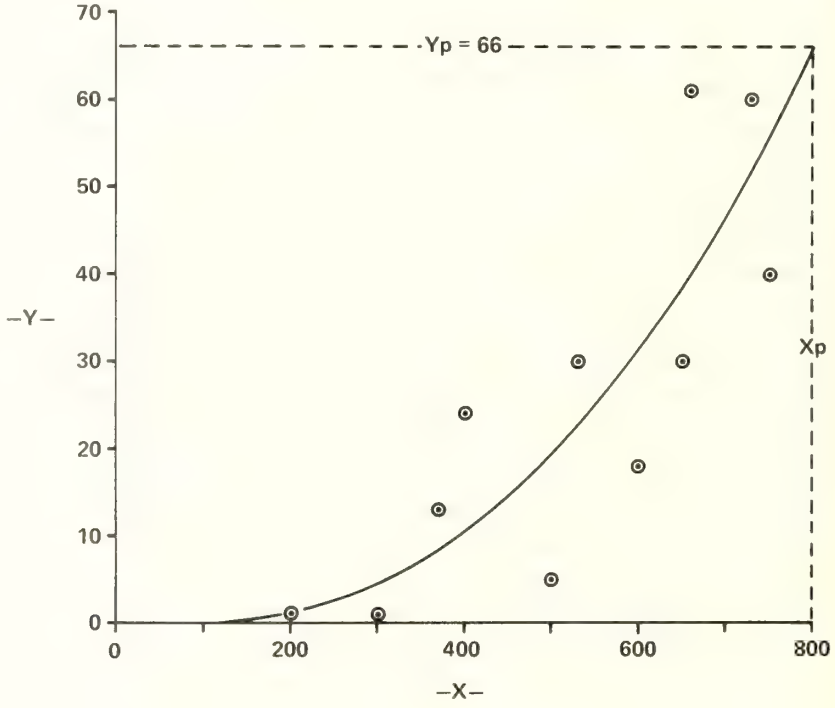


Figure 1.--Here, the expected curve form has been hand-fitted through plotted data points. Plus and minus departures are balanced approximately.

Let's say that an analyst wants to generate an equation for Y from the data set plotted in figure 1. From previous knowledge of the relation between X and Y, he expects the curve to be concave upward with larger values of X. The apparent data trend supports his expectation and he hand-fits such a curve through the data, also shown in

---

[2/]This scaling procedure is identical to that employed for the 1970 companion paper for sigmoids, Matchacurve-1, so the same scaled curve can be compared to the sigmoid standards, if pertinent.

figure 1. This curve then, is to be emulated using the Matchacurve process detailed in the steps below:

1. Let X_p be the value of X at or near the largest X-value in the data set. Let Y_p be the value of Y at X_p. Determine the values of X_p (=800) and Y_p (=66) as shown in figure 1. Note that for sets 1 and 2, Y_p is measured at X = 0 or at X_p depending on position--see table 1. Select representative point coordinates from the smoothed curve.

Five points have been chosen for this example.[3/] Call the array of X values X_i, and the array of Y values, Y_i.

Point coordinates from the smoothed curve.

X_i	0	200	400	600	800
Y_i	0	1.3	10.6	31.4	66

2. Scale the X_i to X_i/X_p and the Y_i to Y_i/Y_p.

Scaled coordinates

$X_i/800$	0.00	0.25	0.50	0.75	1.00
$Y_i/66$	0.00	0.02	0.16	0.48	1.00

3. Plot these points on a sheet of graph paper at the *exact* scale[4/] shown in figure 2. Draw a smooth curve through the points.

4. From table 1, identify the "position"--position A, here--of the scaled curve in figure 2. Then use the scaled curve as an overlay for Set 1 and Set 2 of the Standards, position A; be certain that the X and Y axes are matched exactly. Find the Standards that bracket the overlay curve of figure 3.[5/] In this case, n = 2.5 and 3.0 of Set 1 bracket the overlay curve nicely. Use proportional departure of the overlay curve from the left bracketing Standard to approximate an interpolated value between n = 2.5 and 3.0. This is best done at a point where curve form accuracy is most crucial--the point of sharpest bend was adopted in this case. From figure 3 the interpolated n is 2.7.

[3/]Use fewer points where the desired sensitivity is less, more for greater sensitivity.

[4/]This is the same scale used for the Standards. Note that the odd X scale was necessitated by publication limitations on paper size.

[5/]A light source behind the graphs that are being compared will assist in the matching process.

Table [illegible]

Analyst's curve position	Set	Exponent range	X_p measured at X =	X transform to be fitted by least squares	Sign of B_1 under least squares fit
A	1	[illegible]	X_p	X^n	+
	2	[illegible]	X_p	X^n	
	3	[illegible]	X_p	X^n	+
B	1	[illegible]	[illegible]	$(X_p-X)^n$	+
	[illegible]	As above	0	$(X)^n$	
	[illegible]	[illegible]	[illegible]	$(X)^n$	+
C	1	[illegible]	X_p	$(X_p-X)^n$	-
	[illegible]	As above	X_p	$(X)^n$	+
	[illegible]	[illegible]	X_p	$(X_p-X)^n$	
D	1	[illegible]	0	$(X)^n$	-
	[illegible]	As above	[illegible]	X_p-X^n	+
	[illegible]	[illegible]	[illegible]	$(X_p-X)^n$	-

[1] Unless the specified locations for some of the sets, the X scale must be reversed before applying the exponents as indicated here.

[2] CAUTION: Limits of use for Matchacurve transforms are as follows:

Sets 1 and 2, [illegible] $\leq X \leq X_p$

Set 3, [illegible] $\leq X \leq X_p$

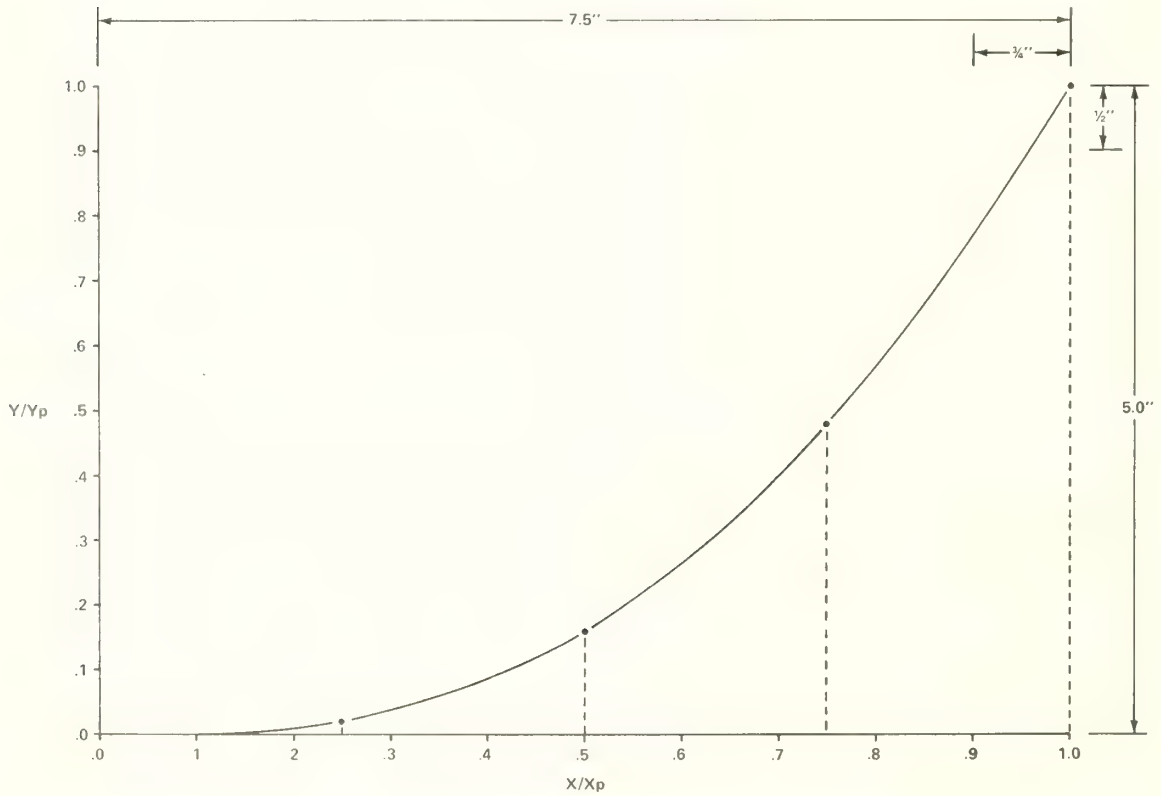


Figure 2.--Here, the graphed curve has been scaled to the Standards.

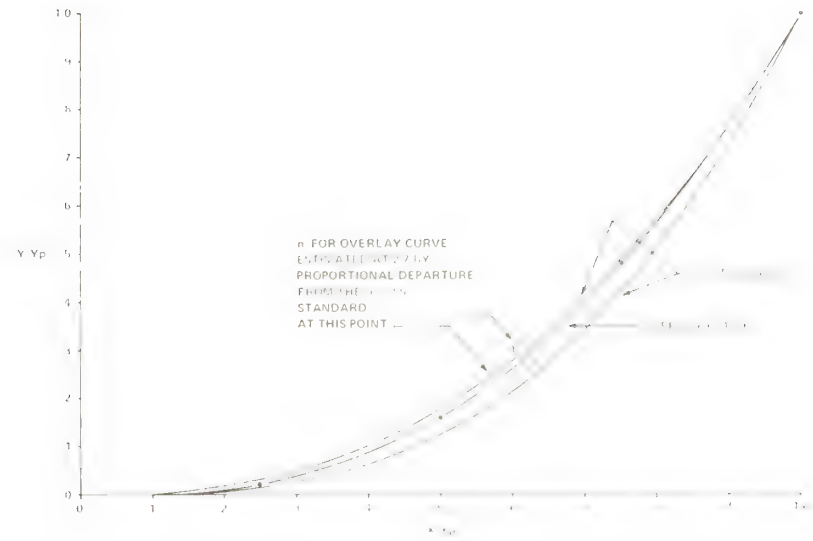


Figure 3.--The Standards best matched to the original curve bracket the overlay curve.

5. Substitute Y for Y/Y_p in the final, simple linear model to be fitted to a relevant data set (the original set is used here) by least squares:

$$Y = B_0 + B_1 X^{2.7}$$

Then the estimated B_0, B_1 -- or $\hat{B}_0$, $\hat{B}_1$ -- will scale the X_i transforms to the Y

It is generally preferable to use a computer for transforming the X_i and applying the least squares fitting process and, in this case, the fitted model is:[6/]

$$\hat{Y} = 2.06 + (0.8932 \times 10^{-6}) X^{2.7}, \quad 0 \leq X \leq X_p$$

The curve for this model is compared to the original graphed curve in figure 4. Differences indicate the extent to which the hand-fitted curve failed to follow the least squares path. We assume here that the least squares curve is the most desirable alternative *within the X-range of the data.*

[6/]Using logarithm tables for the $X^{2.7}$ transforms and a desk calculator for the fittin process, the more laborious hand calculations would be as shown in Appendix B.

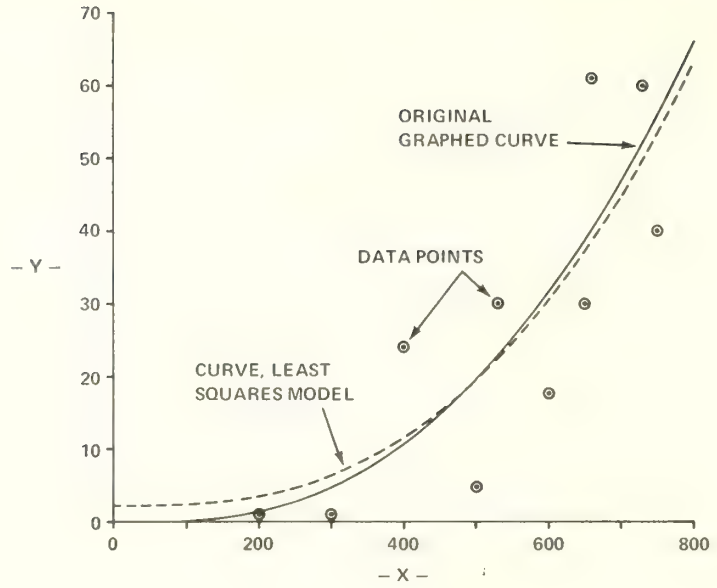
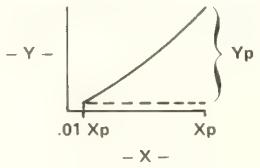
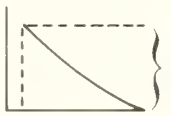
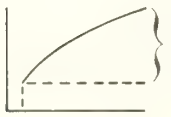
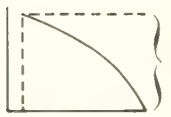


Figure 4.--The fitted model has been plotted over the original graphed form.

The foregoing procedures apply in detail to set 3 with the exception that Y_p is measured as shown in the graphs below:

Position	*Analyst's curve*	Y_p
A		$Y_{X_p} - Y_{0.01X_p}$ *
B		$Y_{0.01X_p}$
C		$Y_{X_p} - Y_{0.01X_p}$
D		$Y_{0.01X_p}$

*Y_{X_p} = Y at X_p, $Y_{0.01X_p}$ = Y at $0.01X_p$

The portion of the curve being "matched" in every position is that over the X-range from $0.01X_p$ through X_p. Be sure to match this X-range of the analyst's curve with the corresponding X-range of the Standards. Adopted transforms from this set apply *only* within the limits $0.01X_p \leq X \leq X_p$.

MISCELLANEOUS NOTES ON MATCHACURVE

- There will be cases where the X transform determined from Matchacurve is not sufficiently accurate to suit the analyst's purposes. In such cases, curve-form description procedures beyond the scope of this paper must be used. For example, refer to nonlinear regression in the text by Draper and Smith.[7]

- The alternative of using a completely automated X-transform selection system from the Matchacurve family of curves was considered. Such a system was bypassed in favor of the graphic comparison technique, which minimizes constraints on curve selection criteria and is still relatively fast to use. It is important to note that selection criteria vary with analysts, analytical objectives, and data characteristics . Our inability even to define applicable criteria commonly used (aside from least squares) discouraged the adoption of complete automation here.

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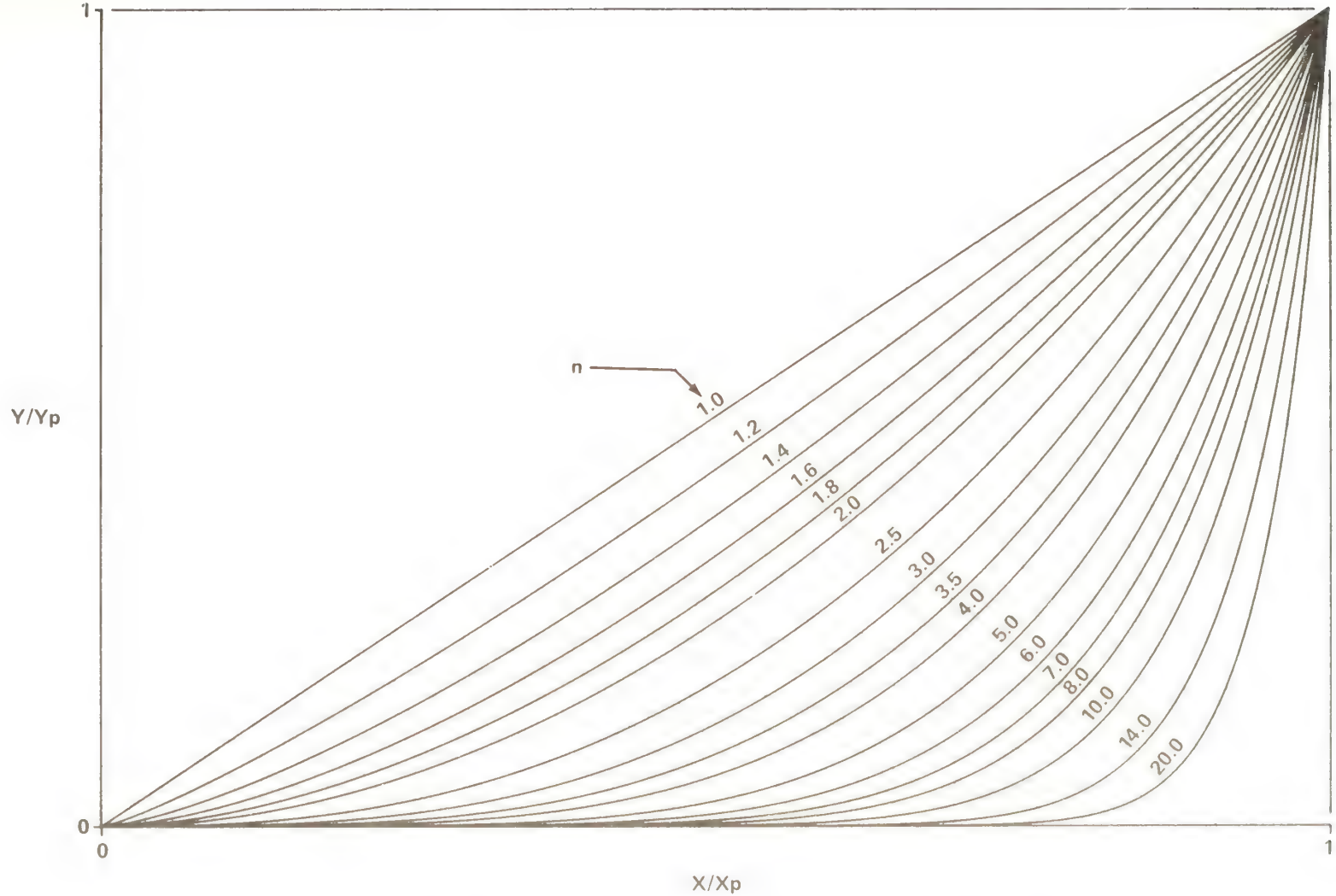
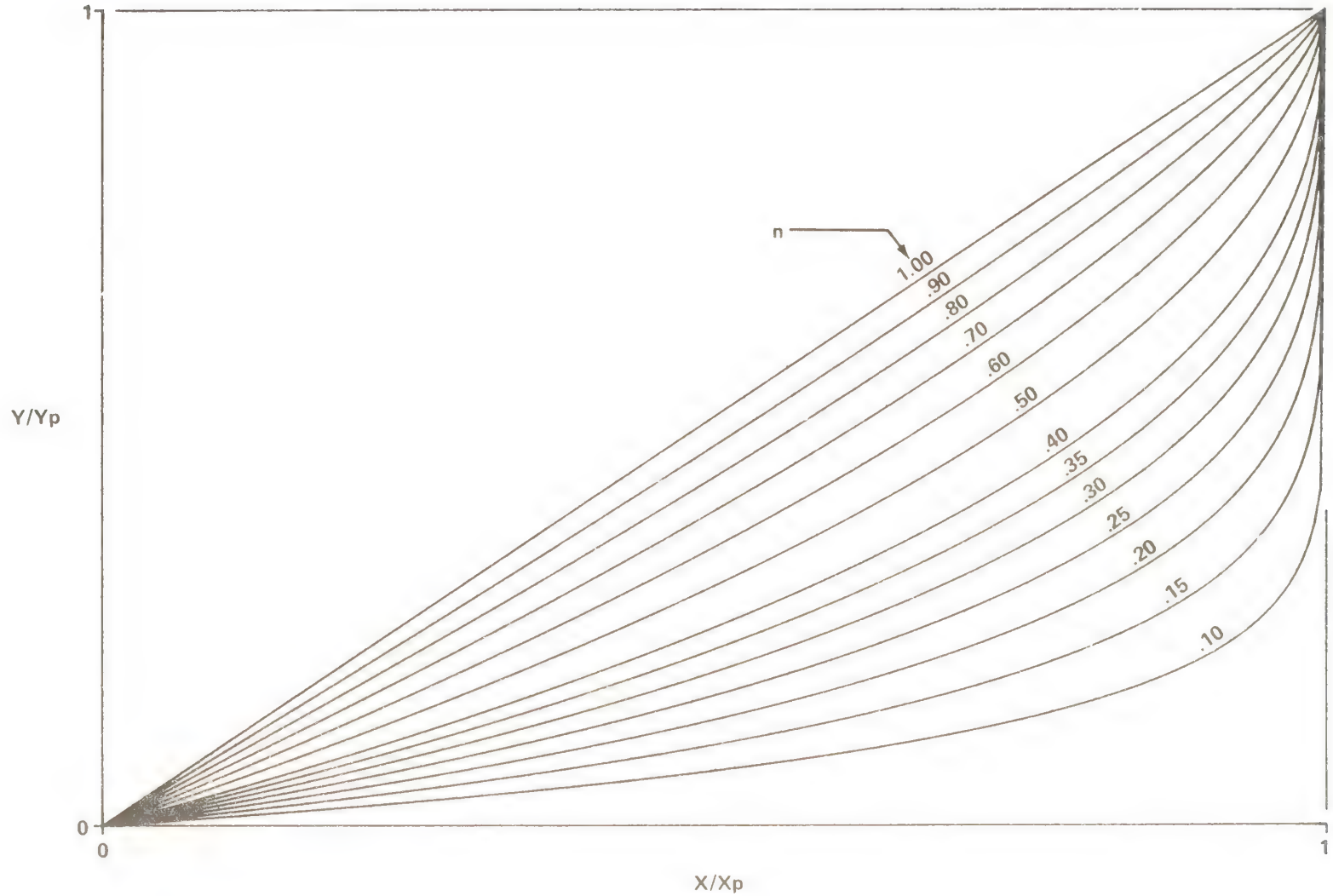
[7] N. R. Draper and H. Smith. Applied regression analysis. New York: Wiley and Sons, Inc. 1968.

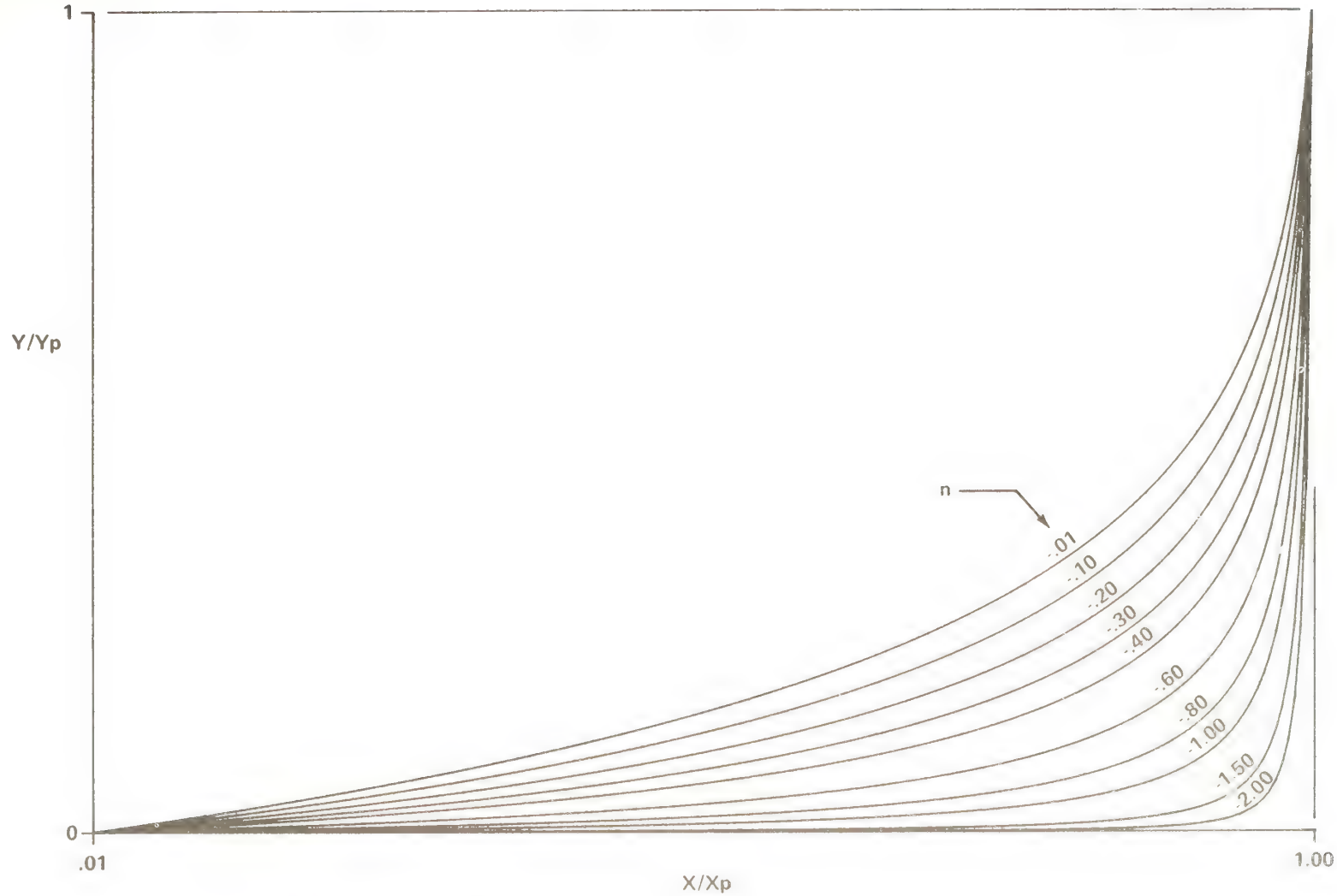
STANDARDS



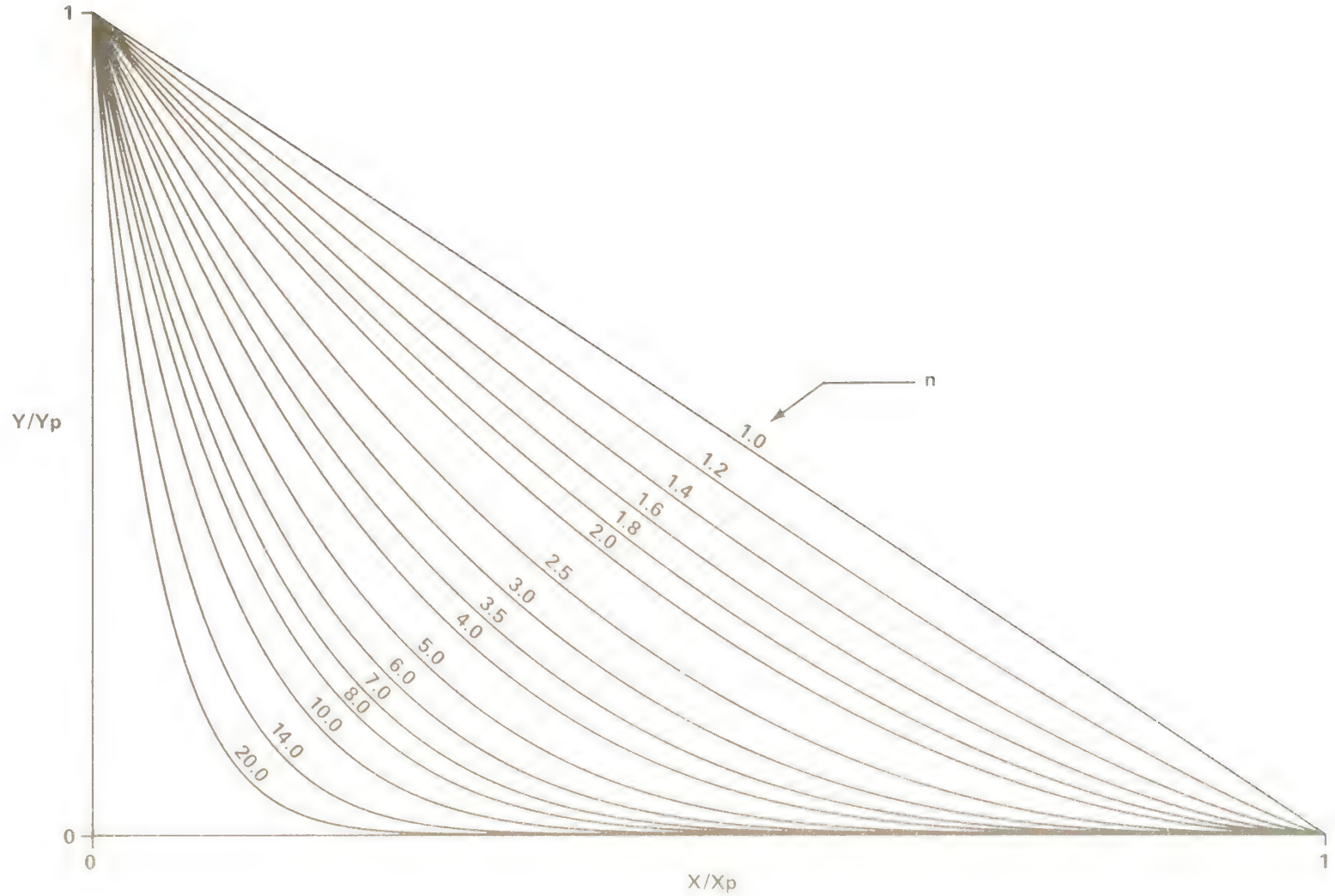
4-1.--Standards for position A, set 1--(X-transform to be fitted by least squares = $(X_i)^n$, $0 \leq i \leq 1$.)

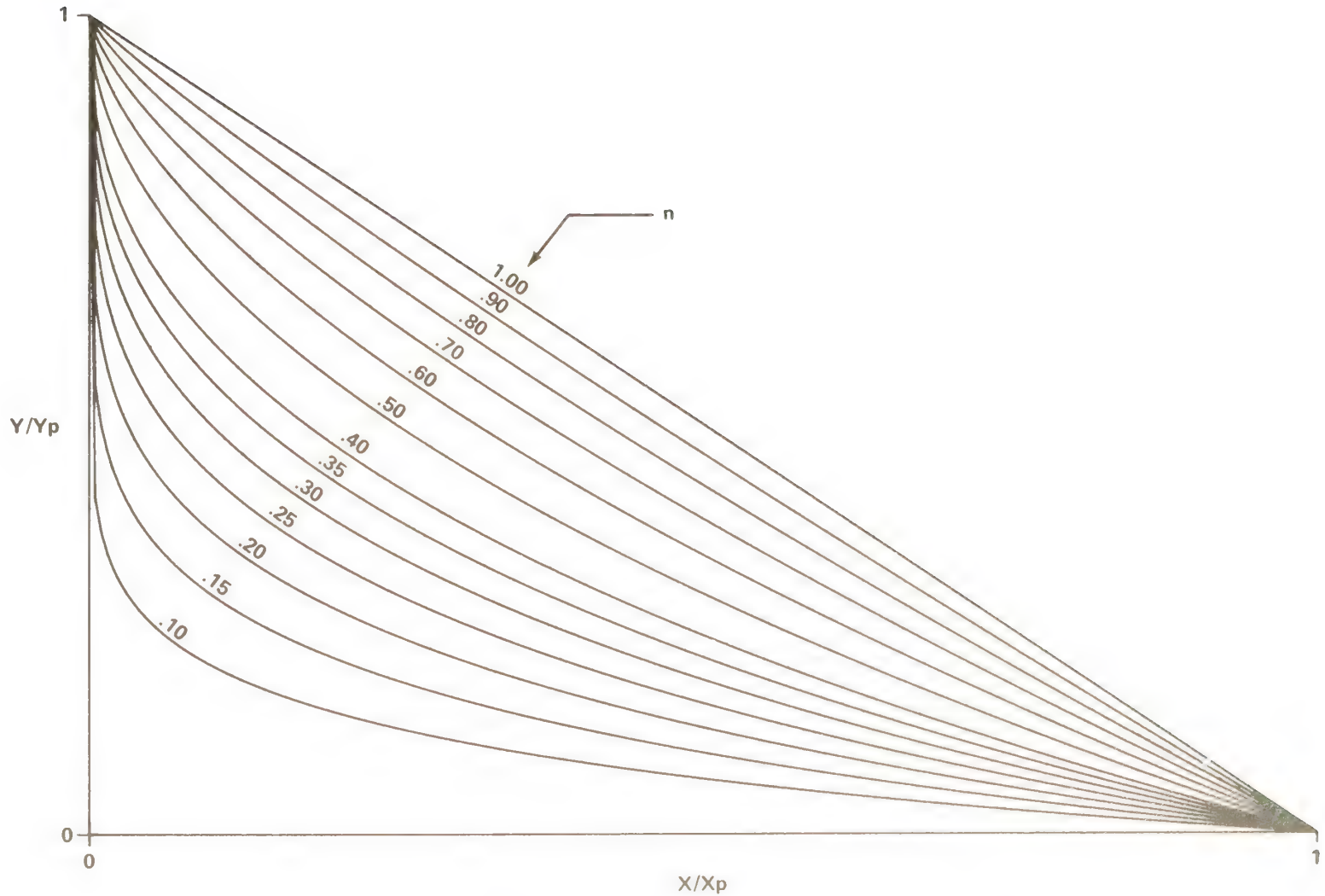


A-2.--Standards for position A, set 2--(X-transform to be fitted by least squares = $(X_2 - X)^n$, $\quad \leq X \leq X_2$)

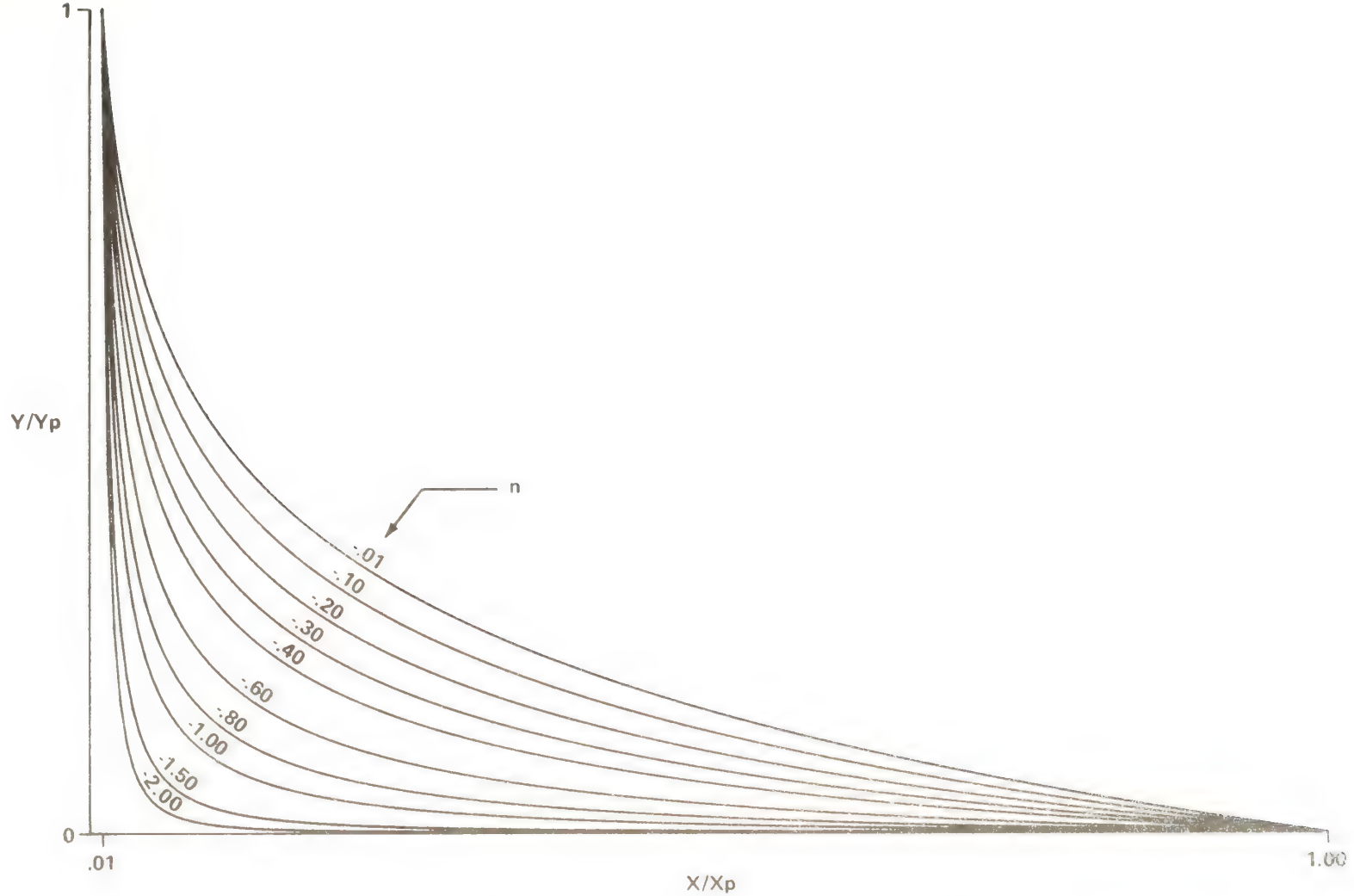


A-8.--Standards for position A, set 8--(X-transform to be fitted by least squares = $(X_p - X)^n$, $.01X_p \leq X \leq X_p$)

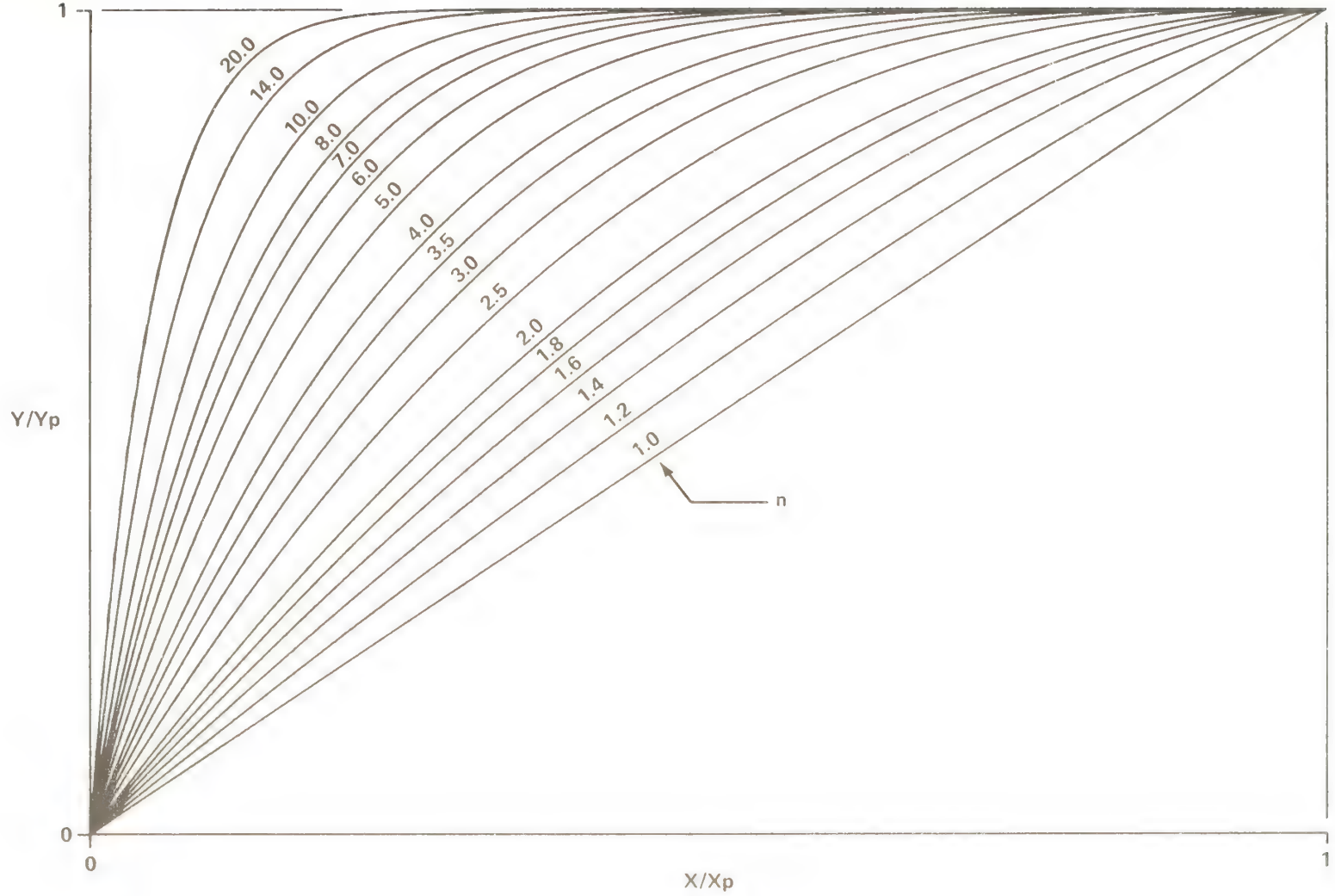

1
Y/Yp
0
0
1
X/Xp
n
1.0
1.2
1.4
1.6
1.8
2.0
2.5
3.0
3.5
4.0
5.0
6.0
7.0
8.0
10.0
14.0
20.0

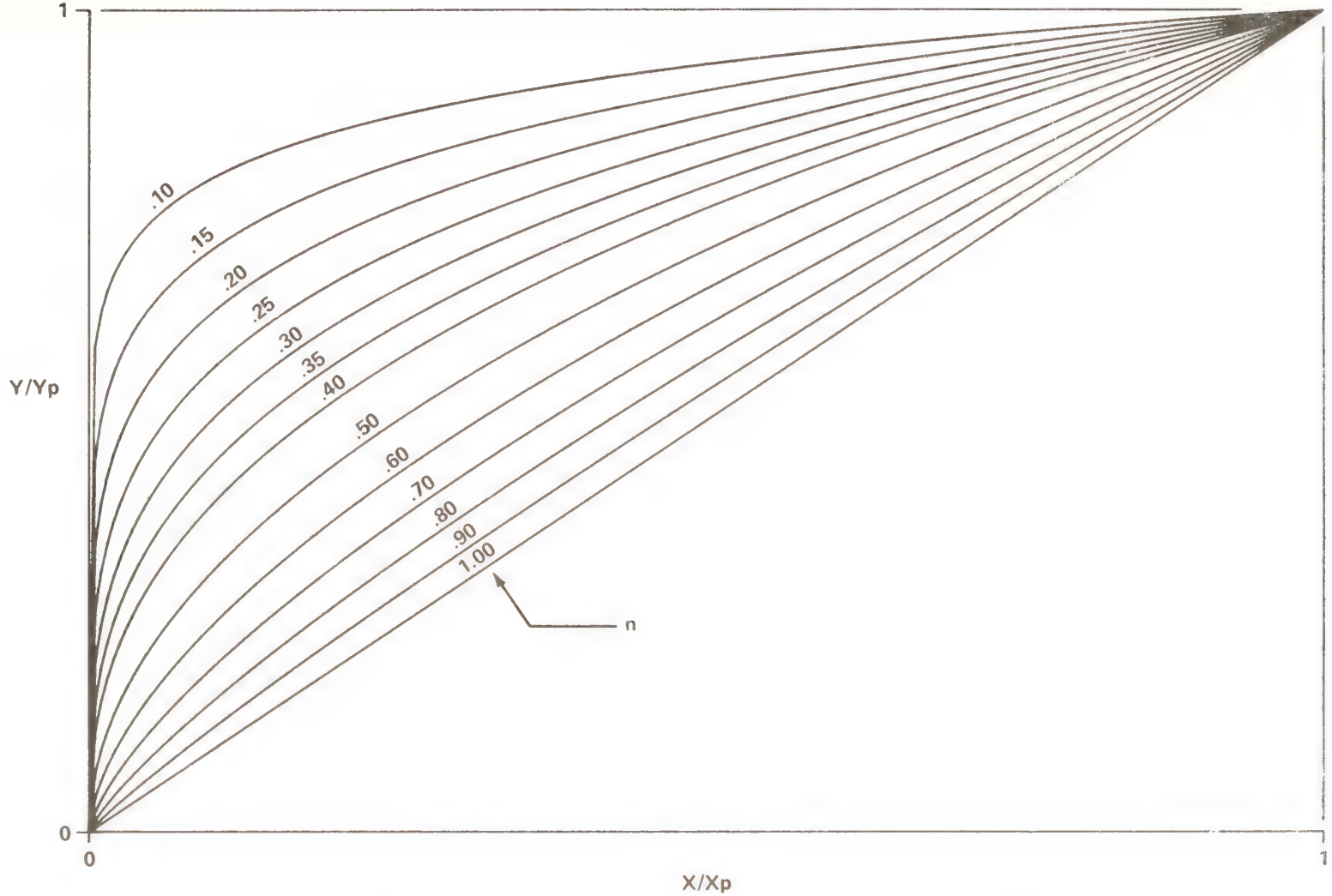


B-2.--Standards for position B, set 3--(X-transform to be fitted by least squares = $(\bar{X})^n$, $0 \leq \bar{X} \leq \bar{X}_p$)

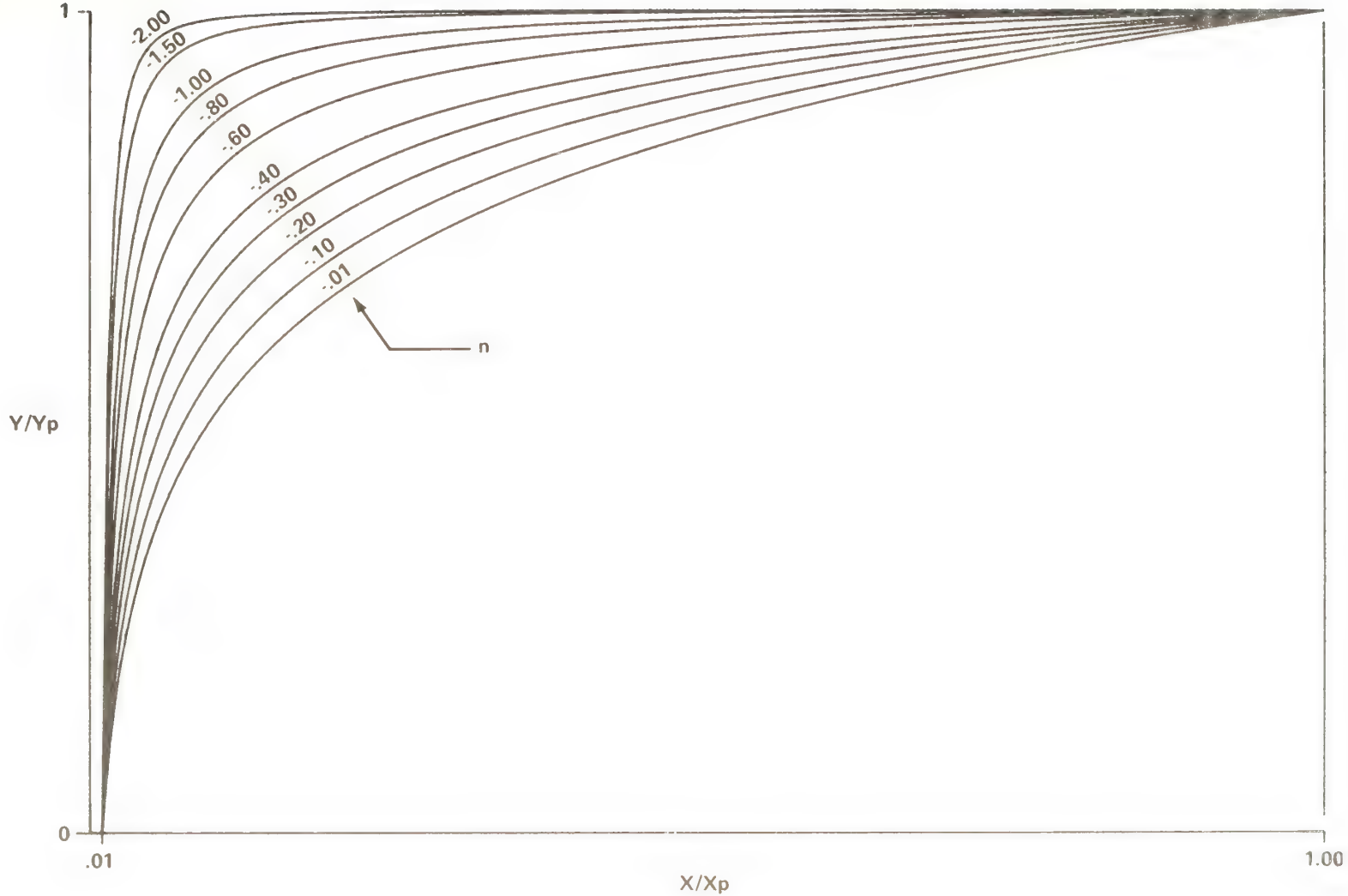


B-8.--Standards for section B, psi δ--(X-transform scale) Stanley [illegible]

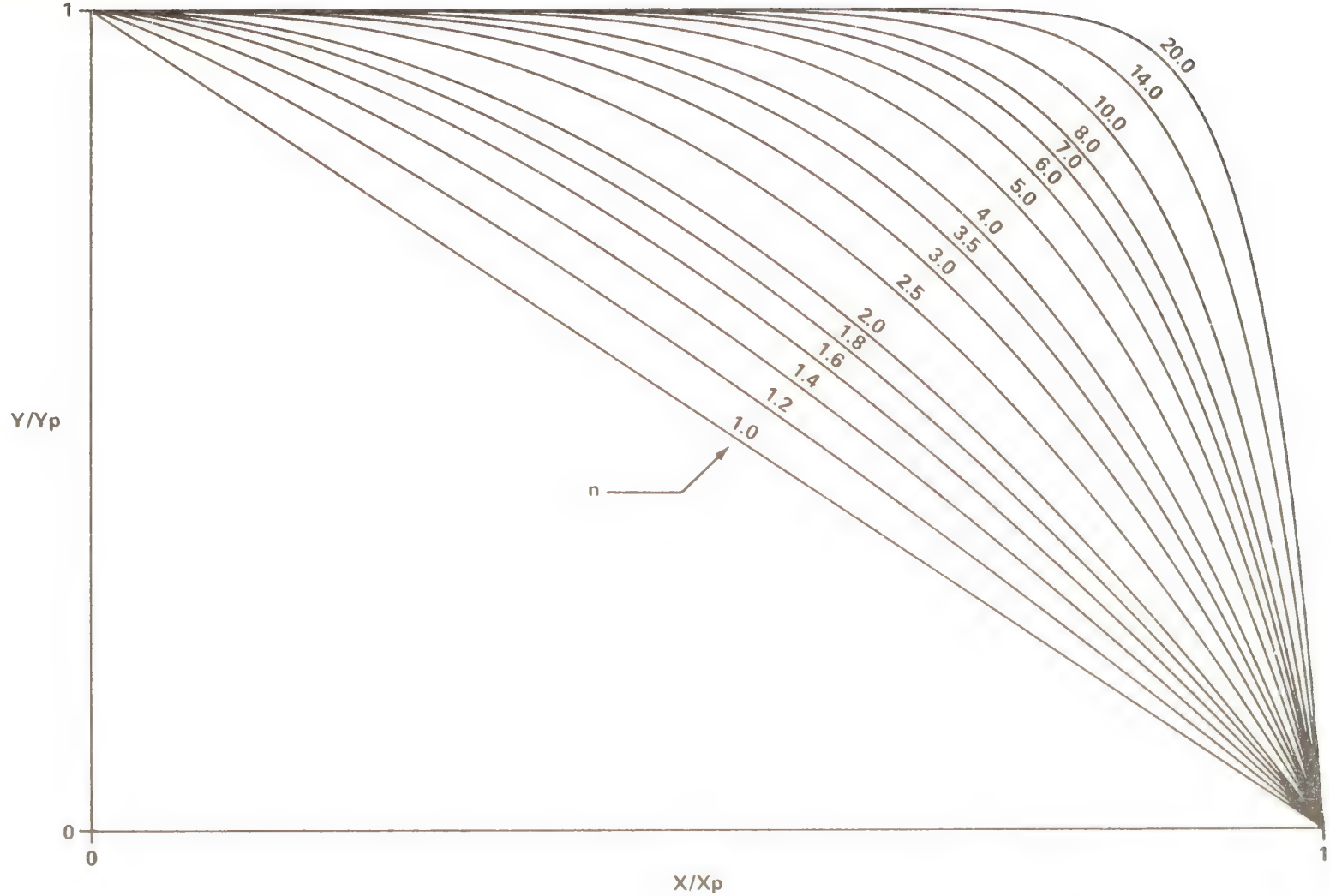

1
0
0
1
Y/Yp
X/Xp
20.0
14.0
10.0
8.0
7.0
6.0
5.0
4.0
3.5
3.0
2.5
2.0
1.8
1.6
1.4
1.2
1.0
n



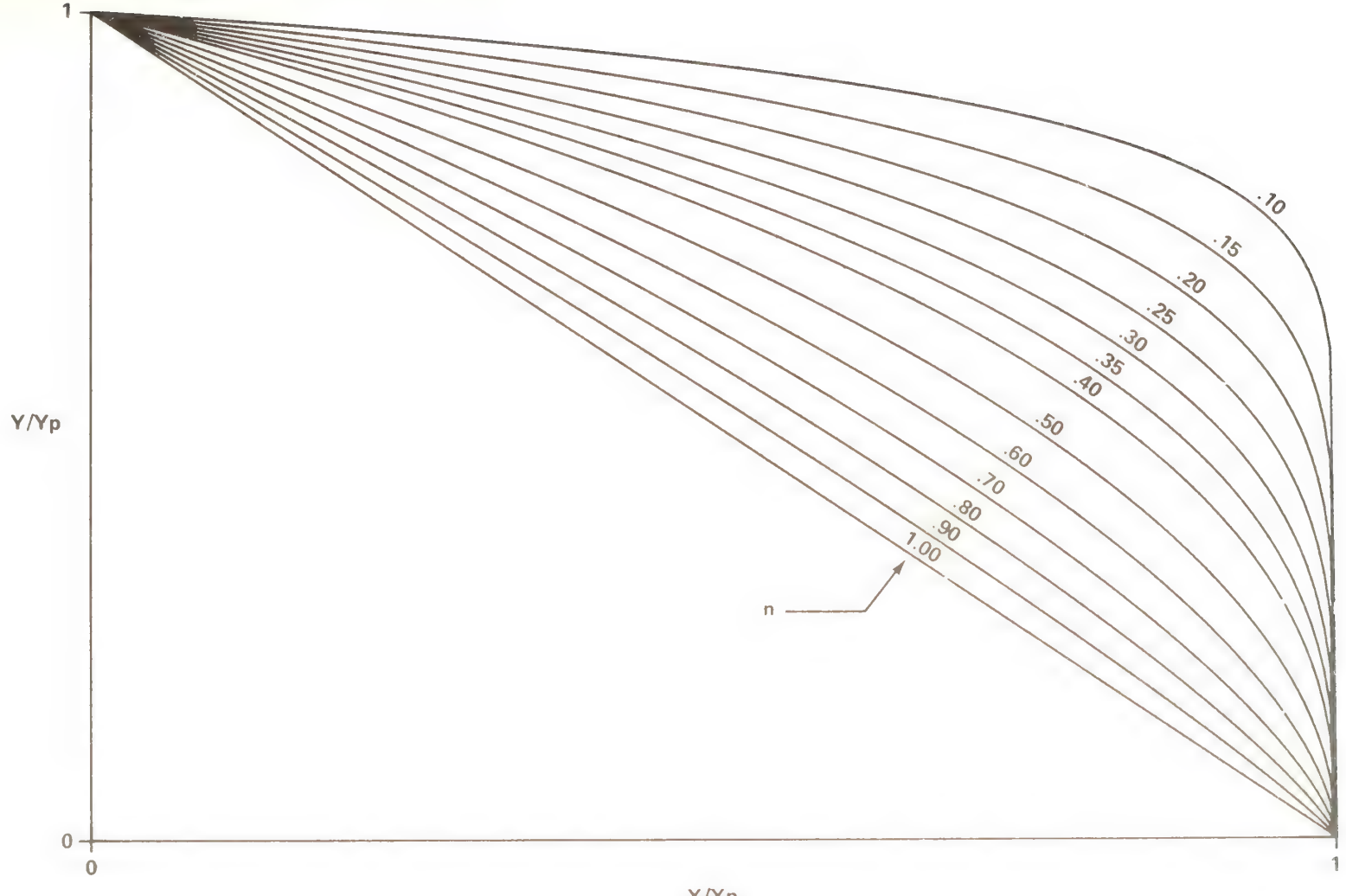
C-2.--Standards for position C, set 2--(X-transform to be fitted by least squares = $(X)^n$, $0 \leq X \leq X_t$)



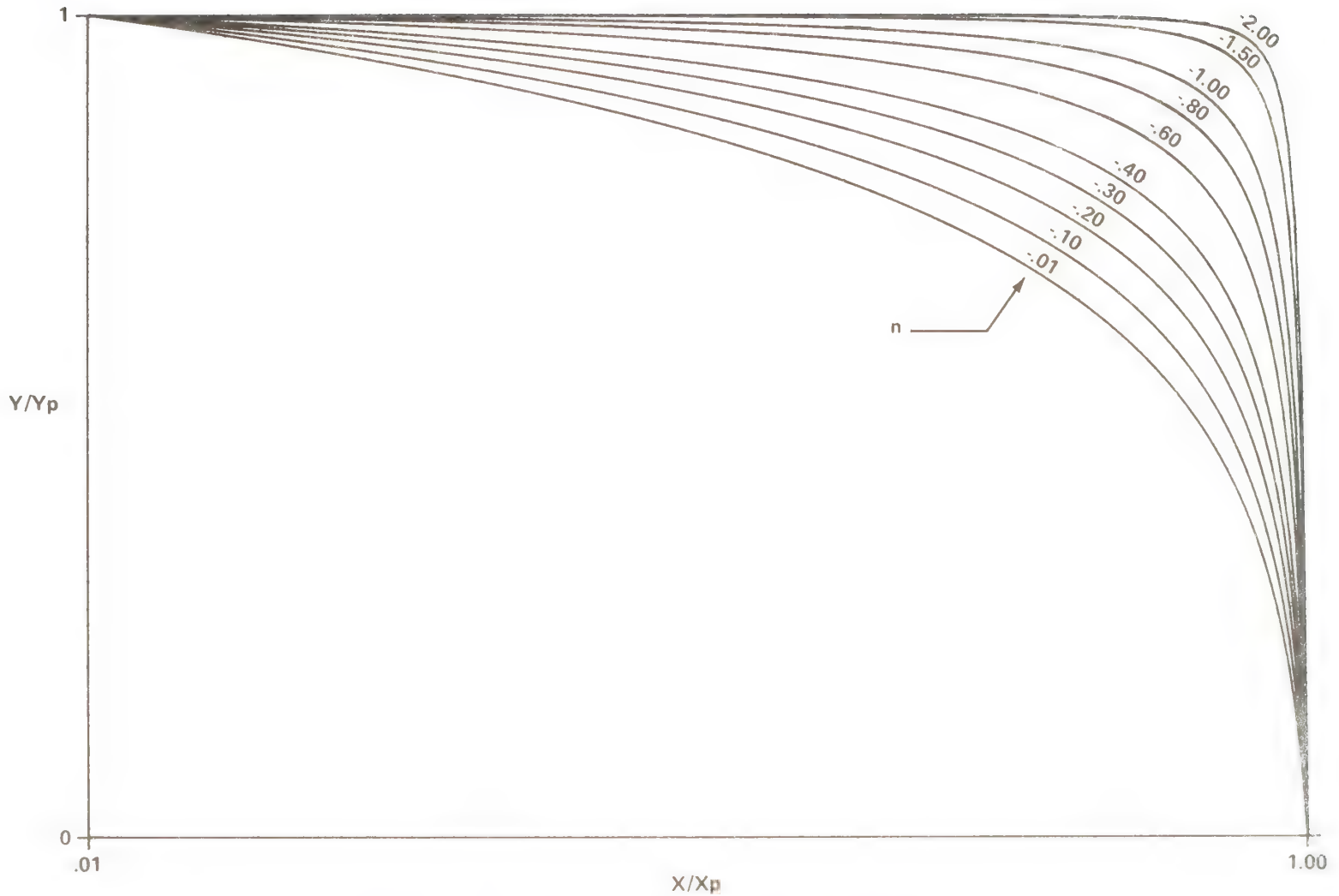
C-3.--Standards for position C, sex δ--(X-transform to be fitted by least squares = $(X)^{n}$, $\cdot 01 \leq X_{p} \leq X_{p}$)



D-1.--Standards for position D, set 1--(X-transform to be fitted by least squares = $(X)^n$, $0 \leq X \leq X_1$)



U-2.--Standards for position P, set 1--(Y-exponent to be fitted by least squares = $\sum(X_i - \lambda)^n$, $0 \leq \lambda \leq \lambda_p$)

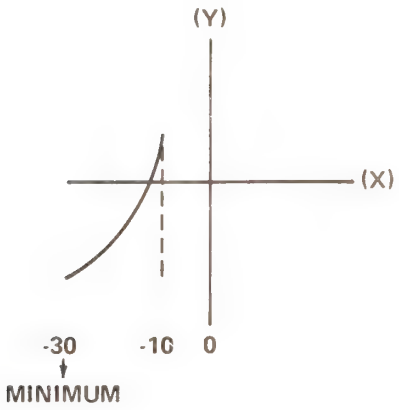


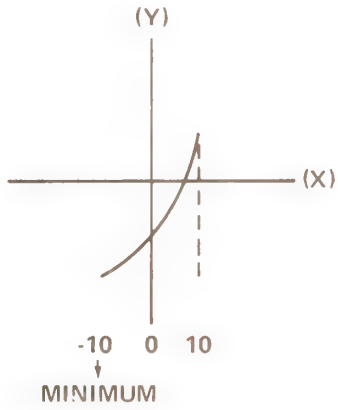
II-3.--Standards for position X, exp. ξ--(X-transform to be fitted by least squares = $(X_i - X)^n$, $.01 X_i \leq X \leq 1.0 X_i$)

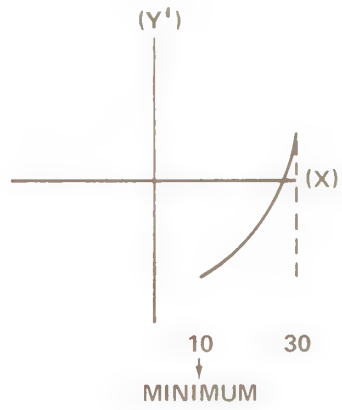
APPENDIX A

ADJUSTMENT OF THE ANALYST'S CURVE TO THE UPPER RIGHT QUADRANT

If the curve lies partly or wholly to either side of X = 0, change the X values of point coordinates from the curve to X' = (X - X minimum)--for example:





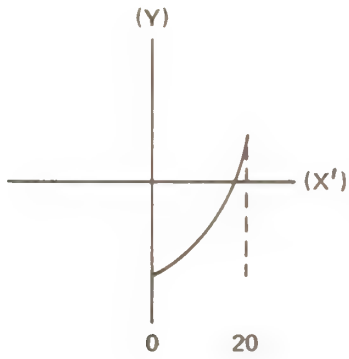


X	X' = X-(-30)
-30	0
-20	10
-10	20

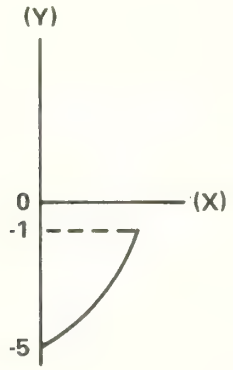
X	X' = X-(-10)
-10	0
0	10
10	20

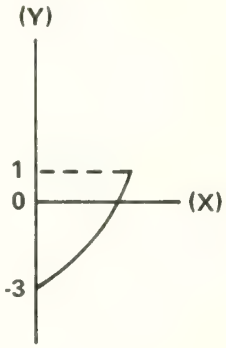
X	X' = X-(10)
10	0
20	10
30	20

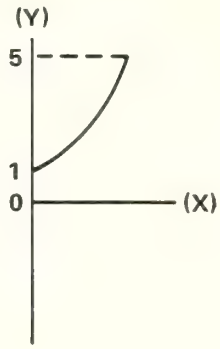
Plotted over X', all three curves would now appear as follows:



If the curve lies either partly or wholly above or below Y = 0, change the Y values of point coordinates from the curve to Y' = (Y - Y minimum)--for example:





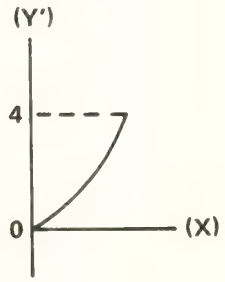


Y	Y' =Y-(-5)
-5	0
-3	2
-1	4

Y	Y' =Y-(-3)
-3	0
-1	2
1	4

Y	Y' =Y-(1)
1	0
3	2
5	4

Plotting Y' instead of Y, all three curves would appear as:



And, last, X' and Y' would be substituted for X and Y, respectively, when looking for a suitable form in the Standards.

In fitting an adopted form to a relevant data set by least squares, always *revert* to the *original* Y_i values--but *retain* any X-transforms in the fitted model. Assume, for instance, that the use of X' = (X + 30) and Y' = (Y + 3) had been necessary to orient the analyst's smoothed curve in figure 1 to the upper right quadrant as shown. The Y-axis would then be labeled Y' and the X axis, X'. All procedures would be identical to those shown for the example except that the final model fitted would be:

$$Y = B_0 + B_1 (X + 30)^{2.7}$$

--and, $\hat{B}_0$ should approximate the constant added to Y in the adjustment process, or, $\hat{B}_0 \doteq 3$.

APPENDIX B

LEAST SQUARES FIT OF EXAMPLE MODEL, HAND CALCULATIONS

Observation	Original data		Let $X^{2.7}$		
number	X	Y	= X'	X'Y	$(X')^2$
1	200	1	0.163229×10^6	0.1632229×10^7	0.2664170×10^{11}
2	300	1	etc.	etc.	etc.
3	370	13			
4	400	24			
5	500	5			
6	530	30			
7	600	18			
8	650	30			
9	660	61			
10	730	60			
11	750	40			
Σ		283	0.2915176×10^8	0.1094696×10^{11}	0.1158486×10^{17}
Mean		25.727	0.2650160×10^8		

Continuing the computations:

$$\Sigma (x')^2 = \Sigma(X')^2 - ((\Sigma X')^2/n) = 0.3859179 \times 10^{16}$$

$$\Sigma (x'y) = \Sigma(X'Y) - (\Sigma X' \Sigma Y)/n = 0.3447002 \times 10^{10}$$

$$\hat{B}_1 = \Sigma(x'y) / \Sigma x^2 = 0.8931957 \times 10^{-6}$$

$$\hat{B}_0 = \overline{Y} - \hat{B}_1 \overline{X}' = 25.72 - \hat{B}_1 (0.2650160 \times 10^8) = 2.06$$

and

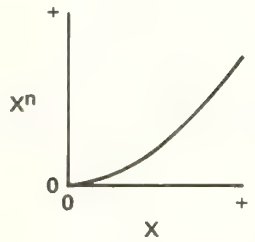
$$\hat{Y} = 2.06 + (0.8932 \times 10^{-6}) X^{2.7}$$

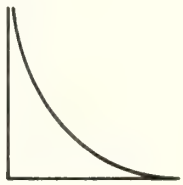
APPENDIX C

DOCUMENTATION OF STANDARDS

Curves of the three exponential sets are oriented in the upper right quadrant as shown below:

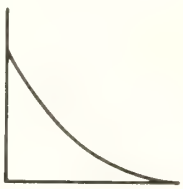
SET		
1	2	3
$1.0 \leq n \leq 20.0$	$0.1 \leq n \leq 1.0$	$-2.00 \leq n \leq -0.01$

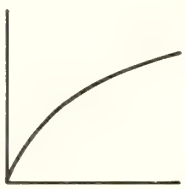


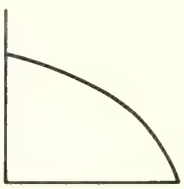


Each of these basic curve types above is presented in each of the four possible positions for the analyst's curve in the upper right quadrant.

A	B	C	D







When the inherent exponential curve position differed from A, B, C, or D, it was necessary to reorient the exponential curve by reversing X-axes and/or rotating scaled X-transforms about Y_p.

The net result was the series of transforms scaled to 1.0 in both X and Y as indicated below:

Position	Set	Plotted form*	Plotting range in X
A	1	$Y = X^n$	0-1.00
	2	$Y = 1-(1-X)^n$	0-1.00
	3	$Y = [(.01^n-1)^{-1}]\ [(1-X)^n-1]$	**0- .99
B	1	$Y = (1-X)^n$	0-1.00
	2	$Y = 1-X^n$	0-1.00
	3	$Y = [(.01^n-1)^{-1}]\ (X^n-1)$	.01-1.00
C	1	$Y = 1-(1-X)^n$	0-1.00
	2	$Y = X^n$	0-1.00
	3	$Y = 1-[(.01^n-1)^{-1}]\ (X^n-1)$	.01-1.00
D	1	$Y = 1-X^n$	0-1.00
	2	$Y = (1-X)^n$	0-1.00
	3	$Y = 1-[(.01^n-1)^{-1}]\ [(1-X)^n-1]$	**0- .99

*These forms were submitted to a computer-controlled plotter to produce the Standards in this paper.

**Although these Standards are actually plotted over the range 0-.99, they are applicable to the range .01-1.00 and were so labeled.

JENSEN C. E. and HOMEYER J. W.

1971. Matchacurve-2 for algebraic transforms to describe curves of the class X^n, USDA Forest Serv. Res. Pap. INT-106, 39 p.

Graphed curves of the class, X^n, can be quickly scaled to and compared with the wide array of standard curves presented. If a standard can be found that suitably matches the scaled curve, the algebraic transform specified for the standard can be applied to the X values of a relevant data set and these can be scaled to their corresponding Y values by least squares to arrive at the fitted model.

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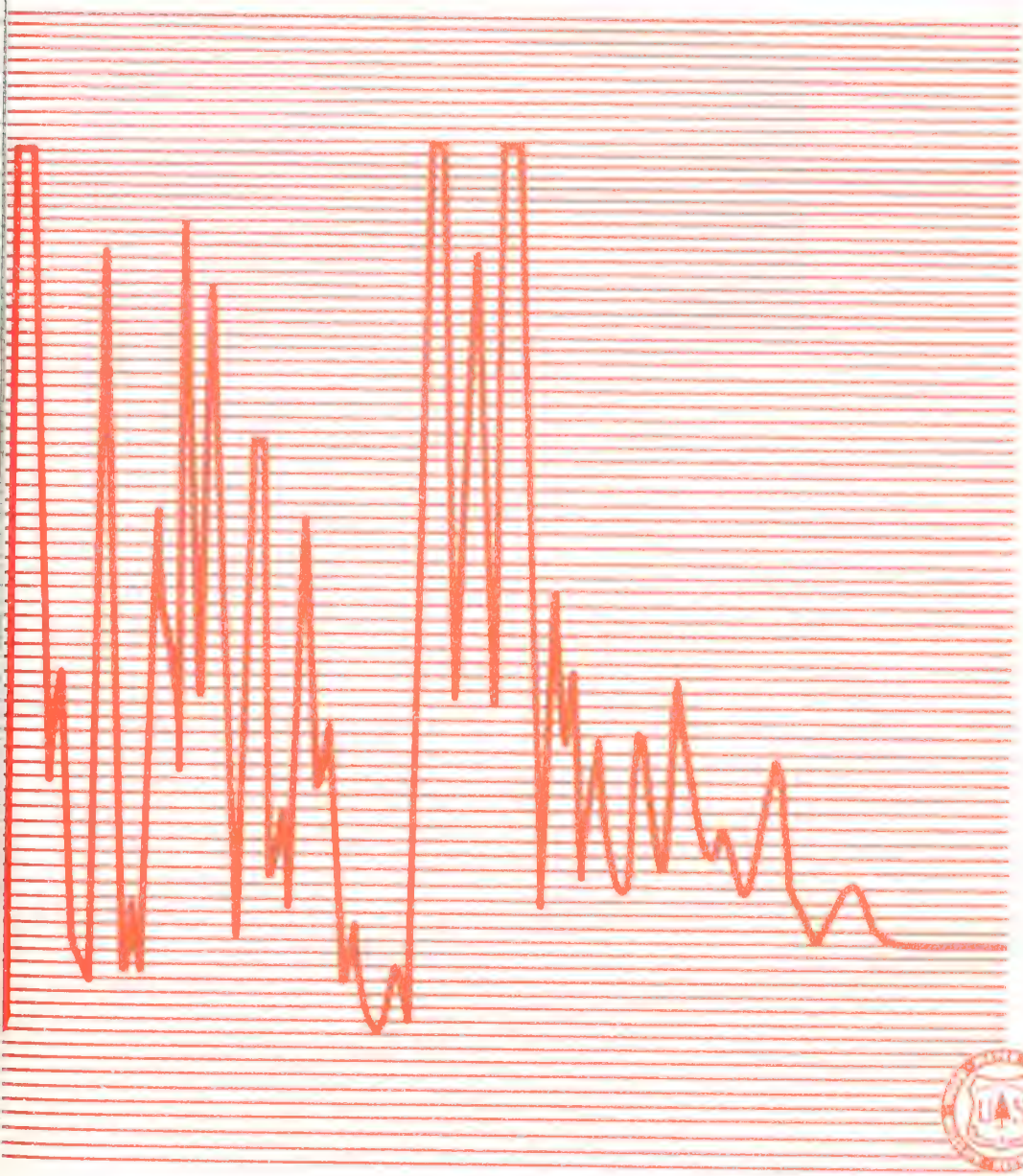
THE PYROLYSIS PRODUCTS AND THERMAL CHARACTERISTICS OF COTTONWOOD AND ITS COMPONENTS

Charles W. Philpot



USDA Forest Service Research Paper INT-107, 1971
INTERMOUNTAIN FOREST AND RANGE
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USDA Forest Service
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September 1971

THE PYROLYSIS PRODUCTS AND THERMAL CHARACTERISTICS OF COTTONWOOD AND ITS COMPONENTS

Charles W. Philpot

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
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I wish to thank Professor F. Shafizadeh, Professor of Chemistry and Forestry, and Dr. G. McGinnis, Research Associate, both of the University of Montana, for their cooperation and help on this study.

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ABSTRACT

This study was undertaken to determine the thermal properties of, and the pyrolysis products from, western cottonwood (*Populus trichocarpa*) and two of its major components: cellulose and xylan. The modifications due to treatment of the wood and its components with an acid and alkali were also documented. Differential thermal analysis (DTA) and thermogravimetric analysis (TGA), as well as direct pyrolysis into a temperature-programed gas-liquid chromatograph, were used in this investigation.

The components of cottonwood were found to generally behave the same in a thermal environment, both in isolated form and when combined in the whole wood. The hemicellulose, xylan, was completely pyrolyzed prior to the onset of cellulose pyrolysis. The acid salt treatment decreased pyrolysis rate of wood, cellulose, and xylan, and increased char, water, and furan compounds while decreasing the major two and three carbon fragments. The alkali treatment also decreased the pyrolysis rate and increased the production of char and water, but decreased the furan compounds while increasing the two and three carbon fragments.

INTRODUCTION

Fire is an integral part of the natural environment and a constant threat to man's surroundings. It has shaped the forests and grasslands and provided mankind with heat, power, and one of his most devastating weapons. In order to understand fire in its many potential roles we must determine the processes involved in conversion of fuels to volatile compounds, which in turn undergo combustion. An essential part of this process is the initial breakdown and pyrolytic reactions of fuel before it burns. This study was initiated, using modern chemical methods, to help lay the groundwork for research leading to the identification of these reactions.

This information will be helpful for coping with the many types of fires which are a major national problem. In the United States over 150,000 persons suffer nonfatal burns each year and it is estimated that 12,500 lives are lost in fires which represent a 5-billion dollar loss (Broido 1965). During 1966, a total of 2,396,550 fires of all types caused $1,860,500,000 in property damage (National Fire Protective Association 1967). This included 970,000 building fires. During the same period, fires burned 4,574,389 acres of forest lands (USDA Forest Service 1967).

The majority of these fires involve wood and wood products, generally referred to as cellulosic fuels. Cellulosic fuels are not flammable as such, but in the presence of a sufficiently powerful source of ignition they undergo pyrolysis and produce volatile compounds which burn in the gas phase and result in the propagation of flaming combustion. The purpose of this study is to identify the major compounds resulting from the pyrolysis of cellulose, hemicellulose, and wood. With the addition of thermalanalysis of these fuels, we hope to determine the interaction among the components undergoing pyrolysis. This should tell us whether studying the thermal properties of the components of wood is a valid technique for the study of the thermal properties of whole wood. Because knowledge of the pyrolysis mechanisms hopefully will lead to the design of efficient flame retardants, a portion of this study deals with the effect of zinc chloride and sodium hydroxide on the pyrolysis of wood and its components.

It is a difficult task to identify these major compounds because of the complex chemical composition of wood, which in addition to cellulose also contains hemicelluloses, lignin, extractives, ash (inorganics), and other extraneous materials. Furthermore, the pyrolysis processes generally involve many concurrent and consecutive reactions. Therefore, the only hope for identifying these mechanisms lies in a systematic approach involving analysis of a selected wood and its components and studying the pyrolytic behavior of each component individually and collectively.

Fire may be defined as the interaction of fuel, energy, and environment. The chemistry of fire deals with the interaction of fuel and energy and consists mainly of the pyrolytic reactions which lead to flaming combustion.

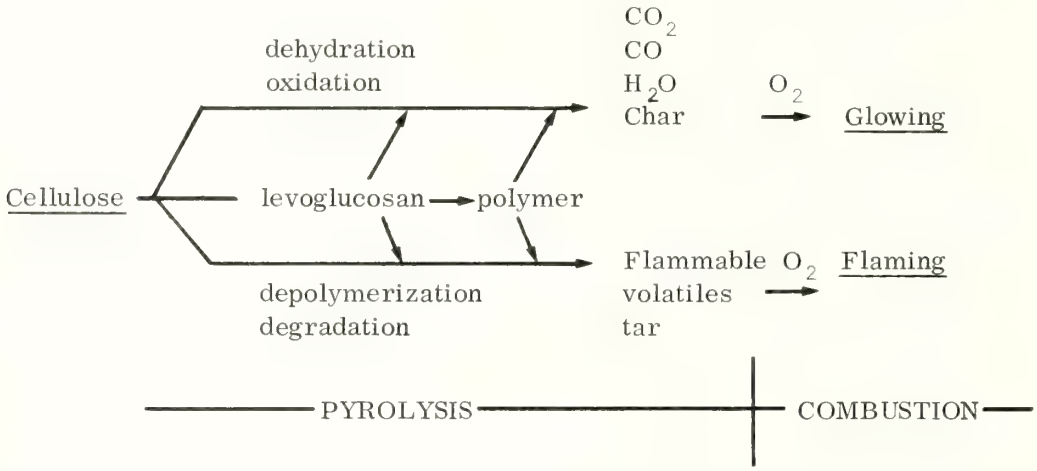
THE PYROLYSIS OF CELLULOSIC MATERIALS

The pyrolysis of cellulosic fuels has been recently reviewed by Shafizadeh (1968). This review covers a broad range of related subjects, including the historical background and the currently available information on the primary and secondary thermal reactions involved in the pyrolysis of cellulose.

Pyrolysis can be simply defined as the thermal degradation of a molecule into various products. The pyrolysis of cellulosic material is defined as the thermal degradation into volatile and nonvolatile products prior to combustion. This means it is usually isolated from combustion by performing experiments in an inert atmosphere or in vacuum. In general the pyrolysis products of wood and wood components are volatiles, tar, and char. The volatile products consist mainly of CO_2 H_2O, various acids, and carbonyl compounds. The tar includes extractives and higher molecular weight degradation products. When cellulose is pyrolyzed, the major component of the tar is 1,6-anhydro-β-D-glucopyranose, commonly known as levoglucosan.

The tar from the xylan component of the hemicelluloses consists mostly of D-xylose dimers and trimers.[1] Char is the carbonaceous residue, the composition of which depends on the extent of pyrolysis.

The pyrolysis of cellulose can be represented graphically as follows:



At temperatures below 250° C. pyrolysis of cellulose occurs very slowly and the main products are CO_2, CO, H_2O, and char. In the presence of O_2 the char could undergo localized surface oxidation or glowing. At temperatures above 320° C. pyrolysis occurs at a much faster rate and leads to the formation of levoglucosan and other volatile degradation products. In an oxygen atmosphere the combustible volatiles burn with flaming combustion. Levoglucosan follows the same sort of route[2] or forms a polymer which can likewise pyrolyze by the two routes.[3] Preliminary work with 4-O-methylglucronoxylan (xylan) has shown this hemicellulose to have the same general action with the exception that no levoglucosan is formed.[4] Levoglucosan has been considered as an intermediate pyrolysis product of cellulose and it has been shown that it could undergo the same type of charring and degradation reactions (Shafizadeh 1968, Ostojic,[2] and Shafizadeh and others[3]).

---

[1]G. D. McGinnis. Pyrolysis of xylan and model compounds. 1970. (Unpublished Ph.D. Thesis on file at the Univ. of Mont., Missoula.)

[2]N. Ostojic. Pyrolysis of levoglucosan. 1970. (Unpublished master's thesis on file at the Univ. of Mont., Missoula.)

[3]F. Shafizadeh, C. W. Philpot, and N. Ostojic. Thermal analysis of 1,6-β-D-glucopyranose. USDA Forest Serv., Intermountain Forest and Range Exp. Station, Ogden, Utah 84401. (Manuscript in preparation.)

[4]McGinnis, op. cit.

The flame retardants enhance charring reactions at the expense of the degradation reactions which produce combustible volatile products.

PYROLYSIS PRODUCTS

A great variety of compounds have been identified among the destructive distillation products of wood and cellulose. Much less is known about the thermal decomposition products of the hemicellulose and lignin. The interest in the pyrolysis of wood originated from the commercial value of naval stores and the destructive distillation products, most of which have been replaced by other chemicals from alternate sources. In 1909 Klason and coworkers identified the products derived from the destructive distillation of cotton cellulose (Klason, Heidenstam, and Norlin 1909); these products are shown in the following tabulation.

Product	[illegible]
Water	34.52
Acetic acid	1.39
Acetone	.07
Tar	4.18
Other organic compounds	5.14
Carbon dioxide	10.35
Carbon monoxide	4.15
Methane	.27
Ethylene	.17
Coke	38.82

Through subsequent research the following products were added to the list: methane formaldehyde; formic acid; acetone; butanone; glyoxal; glycoaldehyde; α-valerolactone; malthol; 2-furaldehyde (furfural); 5-(hydroxy methyl)-2-furaldehyde; methyl furan; 2,5-dimethyl furan; and tri- and tetramethyl furan (Shafizadeh 1968). Schwenker and Beck investigated the products derived from cellulose that were pyrolyzed directly into a gas-liquid chromatograph (Schwenker and Beck 1963). They reported the following major products: fixed gases; formaldehyde; acetaldehyde; water; propionaldehyde; acetone; acrolein; acetic acid; glyoxal; methanol; n-butyraldehyde; butanone; furfural; formic acid; lactic acid; and 5-(hydroxy-methyl)-2-furaldehyde.

Broido and Martin (1961) exposed cellulose sheets to intense irradiation levels of 4.4 to 11.6 cal. $cm.^{-2}$ $sec.^{-1}$ for 0.4 to 0.8 seconds. Using mass spectroscopy, they found the major products to be CO, CO_2, and lesser amounts of H_2, CH_4, C_2H_6, and C_3H_8 in the gases. The liquid phase contained mainly H_2O and small amounts of acetaldehyde, propionaldehyde, butyraldehyde, acrolein, crotonaldehyde, furan, acetone, butanedione, and methanol. The tar was found to be mostly levoglucosan.

Recently Lipska and Wodley (1968) have published the results obtained from a study of isothermal pyrolysis of cellulose in a fluidized bed. The volatile products were resolved with a gas liquid chromatograph (GLC) directly coupled to a mass spectrometer. Figure 1 shows a typical chromatogram from their work. Wodley (1969) has compiled a long list of products that so far have been identified from the pyrolysis of cellulose.

These data indicate that the qualitative and quantitative composition of the pyrolysis products could vary substantially according to the experimental pyrolysis conditions. The most significant variables are the temperature, ambient atmosphere, and the presence of various contaminants or impurities.

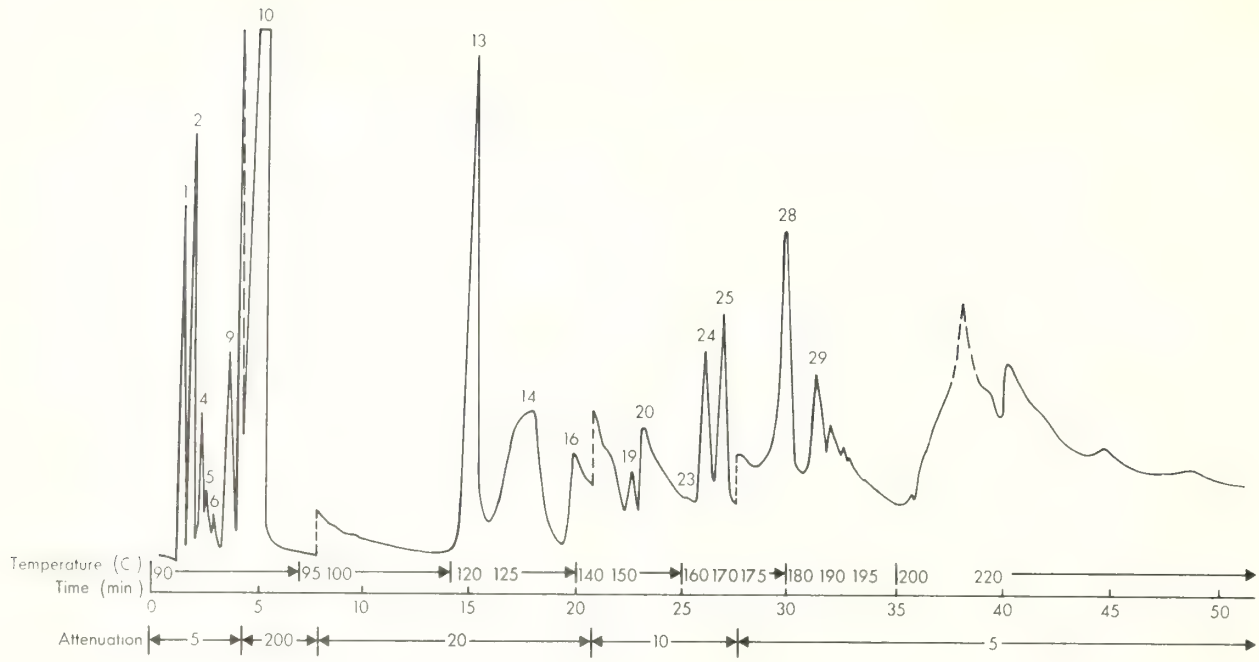


Figure 1.--Chromatogram of cellulose pyrolyzed at 300° C. (Lipska and Wodley 1968). The peaks are (1) fixed gases; (2) acetaldehyde; (4) furan; (5) propionaldehyde; (6) acetone; (9) 2,3-butanedione; (10) water; (13) acetol; (14) methyl formate +; (16) furfural +; (19) propionic acid; (20) formic acid; (23) acetic acid; (24) furfuryl alcohol; (25) butyrolactone; (28) cyclohexanone; and (29) tigaldehyde.

ISOLATION OF THE CHEMICAL COMPONENTS OF WESTERN COTTONWOOD

Western cottonwood (*Populus trichocarpa*) was selected for this study for several reasons. It is currently considered a low-grade western hardwood of little utility but may have future commercial value. The chemical investigations have been limited to certain commercial and biological aspects (Mehring and Schramm 1949; Butin 1960; Mojeika and Sergeera 1957). There has been some reported work dealing with the plenyl glucosides found in the bark (Loeschcke and Franchsen 1964; Pearl and Larson 1965) and some information has also been available on the polysaccharides of the related species, *Populus tremuloides* and *Populus grandidentata* (Jones, Purves, and Timell 1961; Thompson and Wise 1952). This work will greatly increase our knowledge about this potential raw material. Selection of western cottonwood simplifies the investigation procedures because hemicelluloses found in the plant consist mainly of xylan. Another advantage in using this wood is the low content of extraneous materials, especially ash. This helps insure isolation of the carbohydrates in a nearly pure form.

The chemical analysis and isolation of the polysaccharide component of cottonwood were carried out mainly by McGinnis[5] and are reported elsewhere in more detail (Shafizadeh and McGinnis 1971). Further analysis of the inorganic materials was carried out by this author.

A heartwood sample of the cottonwood was analyzed to provide the cell wall polysaccharides and the other components shown in the following tabulation. Hydrolysis

[5]McGinnis, op. cit.

Table 1.--*Inorganic content of cottonwood and the isolated polysaccharide components*

Component	Ash	Ca	K	P	Fe	Na
	- - - - - - - - - - - - *Percent dry weight* - - - - - - - - - - - -					
Wood	0.57	0.059	0.065	0.0122	0.0074	0.006
Extracted wood	.29	.058	.016	.0006	.0057	.006
Holocellulose	1.02	.020	.001	.0014	.0032	[1].394
Cellulose	.15	.002	.002	.0005	.0063	.003
Base-extracted xylan	.15	.001	.001	.0003	.0060	.070
DMSO-extracted xylan	.41	--	--	--	--	

[1]Additions due to base extraction procedure.

of the polysaccharides (holocellulose component) to the sugars indicated the presence of cellulose, "xylan," and "mannan." These polysaccharides were isolated using the procedure of Jones and others (1961). This gave 42 percent cellulose, 18 percent 4-0-methylglucuronoxylan, and 4.1 percent glucomannan based on original wood substance.

Component	*Percent of dry wood*	*Percent of extracted wood*
Benzene-alcohol (2:1) soluble	7.4	
Alcohol soluble	.8	
Total extractives	8.2	
Klason lignin[6]		31.9
Cell wall polysaccharides		76.1

The holocellulose fraction was also extracted with dimethyl sulfoxide (DMSO) to give a small yield of 0-acetyl-4-0-methylglucuronoxylan. This was used for the determination of acetyl groups, which are hydrolyzed under the alkaline condition of the systematic fractionation. Analysis of this product showed 9.9 percent acetyl content.

Hydrolysis of the "xylan" and analysis of the hydrolyzate showed the presence of D-xylose and only a trace of D-glucose impurities. However, as usual, no 4-0-methyl-D-glucuronic acid was detected. The presence of this component was ascertained through methoxyl determination of 4-0-methylglucuronoxylan. This gave a value of 17.5 percent for the uronic acid residue in the acetylated "xylan." On the basis of these data the 0-acetyl-4-0-methylgluronoxylan component contains an average of one uronic acid for each seven D-xylose units and about half of the D-xylose units contain an acetyl group. The glucomannan on hydrolysis provided D-glucose and D-mannose in the ratio of 1:1.

The composition of inorganic materials found in the original wood as the ash content and composition of these materials in the isolated cell wall polysaccharides as impurities were analyzed as a part of this study. This analysis was carried out with flame photometry for calcium, potassium, and sodium. Iron and phosphorus were determined by colorimetry following wet digestion. The data are presented in table 1 and this information is used for determining the effect of inorganic materials on thermal decomposition of wood and the effect on related cell wall polysaccharides. This information will also allow comparison with other thermal analyses reported in the literature.

[6]Includes acid decomposition products.

THERMAL ANALYSIS

Thermogravimetric analysis (TGA) and differential thermal analysis (DTA) are commonly used to assess the thermal behavior of materials. The rate at which a material volatilizes as the temperature is raised in a controlled environment is shown by dynamic TGA. A small sample (usually <1 g.) is placed in the pan of an electronic balance suspended in a heated tube. As the system is heated, the weight loss of the sample is continuously recorded against temperature. In DTA a small sample and an inert reference material are heated in a silver block. As the heating continues at a constant rate, the sample undergoes various exo- or endothermic reactions or phase changes, which are detected in comparison with the inert material. The combination of DTA and TGA in conjunction with chemical methods provides a tool for detecting the nature of the pyrolytic reactions.

The thermal analysis curves can be analyzed through the following characteristics:

1. The initiation temperature, (T_i), or the onset of pyrolysis, as indicated by the beginning of weight loss on TGA, and/or the appearance of a peak on DTA;

2. The rate of weight loss, (R), shown by the slope of the TGA curve;

3. The residue (char), (C_T), remaining at a given temperature, (T), but normally after the period of rapid pyrolysis;

4. The temperature at which the peaks representing the endo- or exothermic reactions occur and the relative value of the enthalpy indicated by the area under the peak.

Thermal analysis is used for detecting the chemical kinetics and the energy of activation of the pyrolysis process. This would be valid if it is assumed that pyrolysis is a single reaction. However, nothing could be further from the truth. What actually is measured is the rate of weight loss caused by evaporation of numerous pyrolysis products.

Despite the fact that the data from thermal analysis describe the net effect, the characteristics which are tabulated above could be used for describing the general pyrolysis behavior of the substituents. The main objective of this analysis is to point out these characteristics and indicate how they are related to the thermal behavior of the original material.

Tang and others (Tang and Eickner 1968; Shafizadeh 1968) have found that the flame retardants generally decrease the rate of pyrolysis, R, in a dynamic environment, lower the initiation temperature, T_i, and increase the char, C_T.

Recently, Philpot has shown that the amount of silica-free minerals (SFA) in plant material could be correlated with the pyrolysis characteristics. A direct log-log relationship was found between SFA and maximum pyrolysis rate. The temperature at which the characteristic cellulose endotherm appeared showed a high correlation (R^2 = 0.91) with the SFA of the plant material. The char remaining at 400° C. could also be correlated with mineral content. There was some indication that the effect of the inorganic materials on the course of the pyrolytic reaction could vary according to the composition of the minerals.

The following procedures were used for obtaining the thermal analysis data. The thermal properties of cottonwood and its components were investigated by thermogravimetric analysis (TGA) and differential thermal analysis (DTA). These data were obtained

with a DuPont Model 900-950 thermal analyzer, programed at the rate of 15°/minute. The experiments were conducted in a nitrogen atmosphere, using silica beads as the reference for DTA and 5 or 10 mg. of the groundwood or its components as the sample. For TGA the gas flow was regulated at the rate of 100 ml./minute. Because Klason lignin is condensed and altered under the drastic acid treatment, it was augmented with milled wood lignin which is much closer to the native material (Browning 1963). The results obtained are shown in figures 2 and 3.

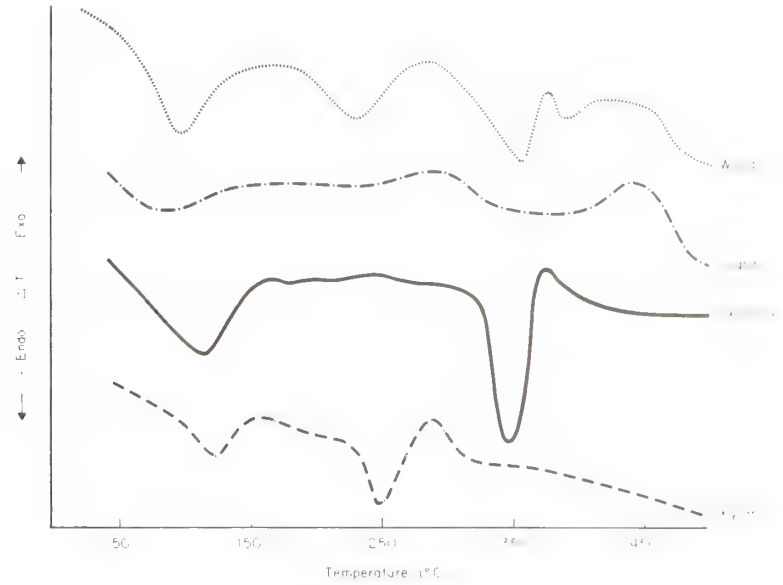


Figure 2.--Differential thermal analysis of cottonwood, cellulose, xylan, and lignin.

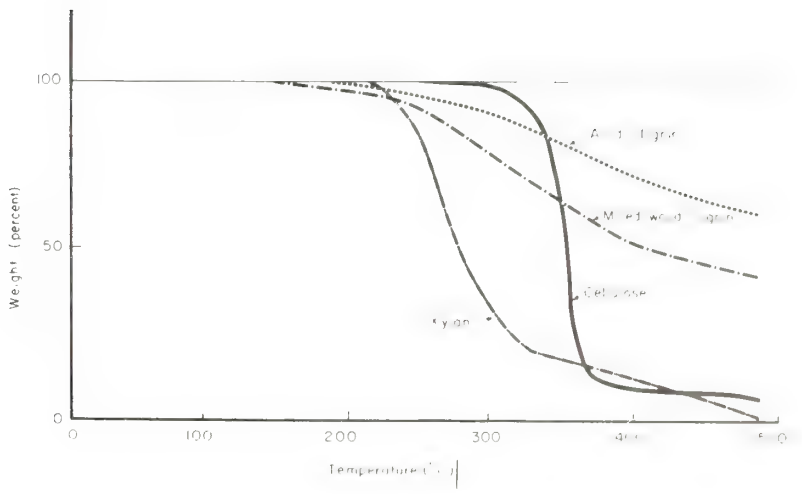


Figure 3.--Thermogravimetric analysis of cottonwood, cellulose, xylan, and lignin.

A summary of the thermal characteristics of cottonwood and its components are presented in table 2. These data indicate that the thermograms of cottonwood reflect the thermal behavior of its major components and the information that is obtained on these chemicals could be extrapolated to the original material with confidence. These data also show that under the experimental conditions (uncatalyzed reactions) lignin is the major source of char, but the carbohydrates are the precursor of the volatile products (tar and gases).

Table 2.--*The pyrolysis characteristics of cottonwood components*

Component	Temperature of initiation (T_i)	Maximum rate of pyro (R)	Residue at 450° C.
	°C.	*mg./°C.*	*Percent*
Wood	175	([1])	19
Cellulose	320	.25	6
Xylan (DMSO)	215	.11	6
Milled wood lignin	175	.03	45
Acid lignin	200	.02	60

[1]Wood exhibits two definite rates, one during xylan pyrolysis, the other during cellulose pyrolysis.

The most significant point about these data is the importance it places upon the pyrolysis of hemicellulose. Beall[7] touched on this when he concluded, "The hemicelluloses appear to be the most important component in determining the rates of degradation of both softwoods and hardwoods." In addition to this we can see that xylan pyrolyzes almost completely prior to the beginning of pyrolysis of cellulose. Cellulose has been studied quite extensively in terms of ignition and other phenomena. It is quite clear that the hemicelluloses are of at least equal importance and may even provide the initial volatiles for ignition and combustion.

PYROLYSIS OF COTTONWOOD CELLULOSE

In this part of the current study the pyrolysis products from cellulose and the changes due to treatment with $ZnCl_2$ and NaOH were qualitatively and quantitatively determined under identical conditions in order to: (1) determine the effects of an acidic and an alkali additive on the composition of the volatile products and the pyrolytic reactions; (2) gain basic information about the mechanisms of the reactions involved by comparing these data with similar data from levoglucosan; and (3) extend the information that has been obtained from wood in which cellulose forms the major chemical component. Levoglucosan, 1,6-anhydro-ß-**D**-glucopyranose, is currently being studied as a model compound for the secondary pyrolysis reactions of cellulose.

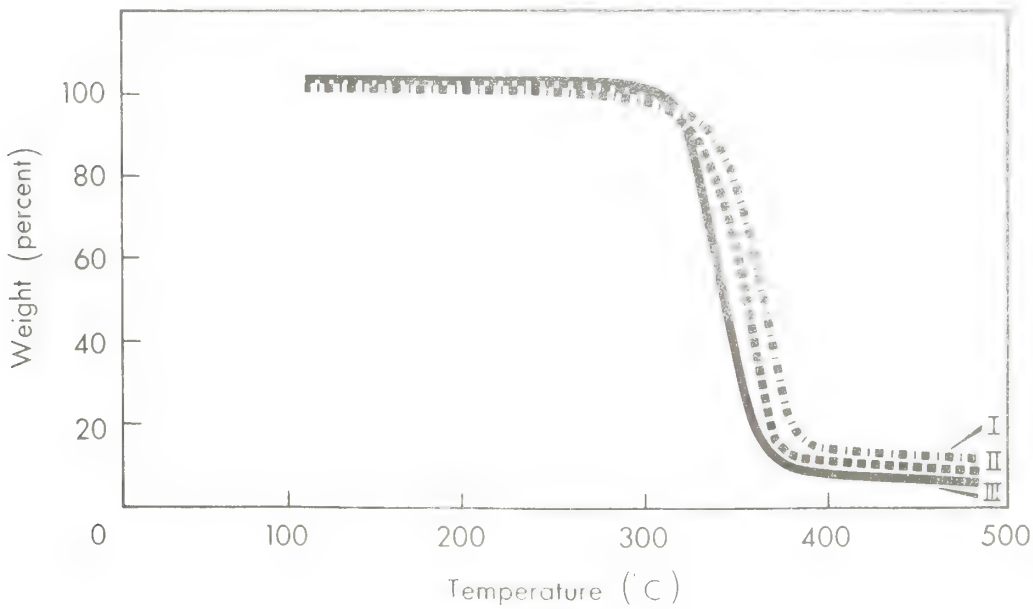
Treatment of cellulose consisted of adding 5 percent by weight of anhydrous zinc chloride or sodium hydroxide to a powdered sample. A small quantity of tetrahydrofuran was added to help evenly distribute the treatment. The treated material was then dried and stored under vacuum. The treatment procedure for both DMSO and base xylan was similar except it was found that about four-fifths of the sodium hydroxide was neutralized, probably by the glucuronic acid component. Therefore, 9 percent sodium hydroxide was used for alkali treatment of xylan.

[7]F. C. Beall. Thermal degradation analysis of wood and wood components. 1968. (Unpublished Ph.D. Thesis on file at Syracuse Univ., N.Y.)

Before investigating the effect of additives, it was desirable to determine the effect of the ash or natural inorganics on the pyrolysis of cellulose. Broido (1966) has pointed out that a contamination as little as 0.1 percent can significantly change the TGA of cellulose. Shown in figure 4 is a comparison of: commercially purified cellulose, ash content 0.01 percent;[8] cotton cellulose, ash content 0.08 percent; and cottonwood cellulose, ash content 0.15 percent. This TGA shows cottonwood cellulose to behave differently than the "ash free" product and to behave similarly to the cotton cellulose with 0.08 percent ash.

As cellulose is heated from ambient to 500° C., the TGA and DTA curves clearly show the net effects. Cellulose had a maximum pyrolysis rate of 0.25 mg./°C. and a residue of 6 percent at 450° C. shown by TGA (fig. 5). The temperature of the beginning of active pyrolysis was 320° C. shown by TGA (fig. 5). The first endotherm corresponds to water loss and the second endotherm corresponds to major weight loss of the sample. A small exotherm is apparent subsequent to the second endotherm; it occurs at the secession of rapid weight loss.

The effects of $ZnCl_2$ on cellulose shown by TGA and DTA are to reduce the pyrolysis rate, lower the initiation temperature, and increase the residue. On the DTA curve (fig. 5), the major endotherm was somewhat reduced in size and the peak temperature was lowered drastically.



(I); cottonwood cellulose, ash content 0.15 percent (II); and commercial "ashless" cellulose, ash content 0.01 percent (III).

[8]Analytical filter pulp manufactured by Carl Schleicher and Schuell Co.

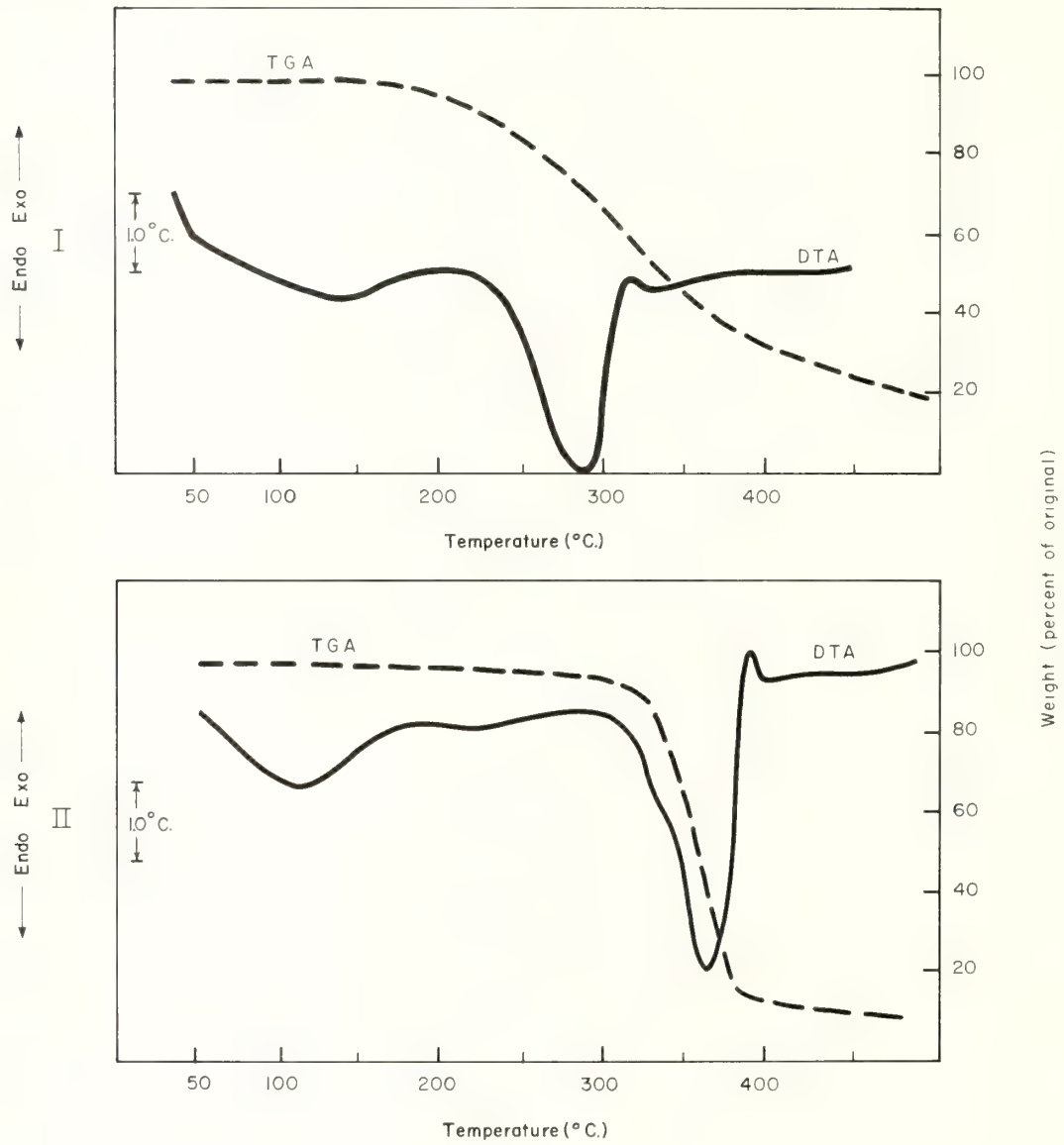


Figure 5.--Thermograms of cellulose (II) and cellulose treated with 5 percent zinc chloride.

The changes caused by NaOH are dissimilar to those caused by $ZnCl_2$. The TGA shows the rate of weight loss to be slower for alkali treatment and the residue to be greater (fig. 6). On DTA an apparent exotherm, beginning at 175° C., occurred, which was followed by a much reduced endotherm as compared to untreated cellulose. A large exotherm occurs from 275° to 350° C. and is the major difference between the two treatments. This is in agreement with the results of Mack and Donaldson (1967) for base treated cellulose. Table 3 lists the thermal properties of treated and untreated cellulose.

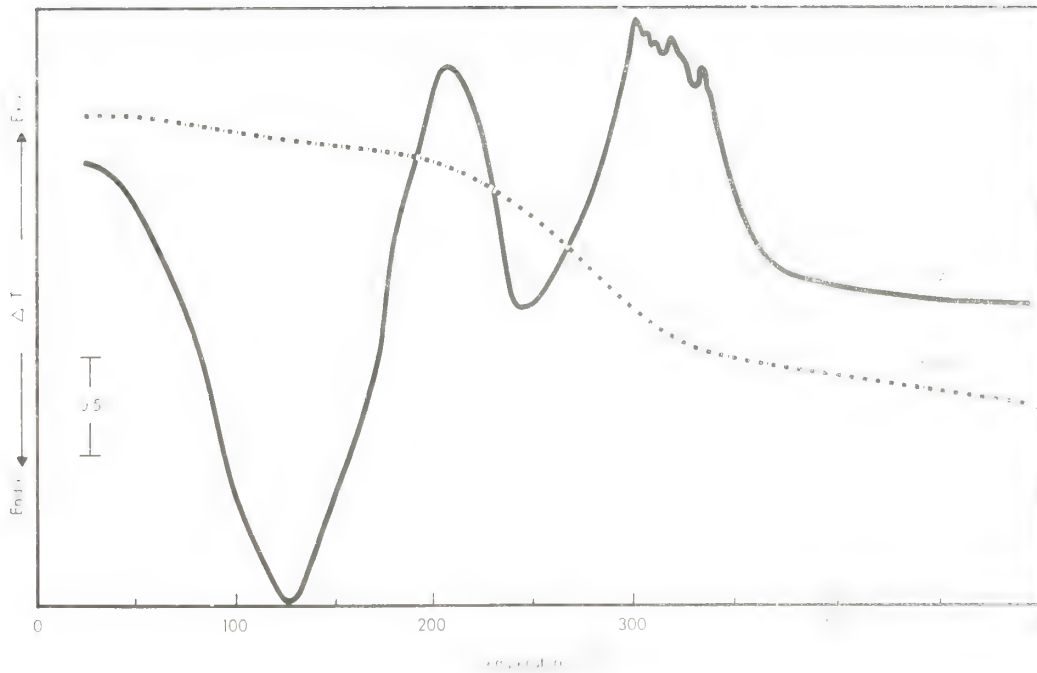


Figure 6.--Thermogram of cellulose treated with 5 percent [illegible]

Table 3.--*Some thermal properties of cellulose and cellulose treated with 5 percent $ZnCl_2$ or 5 percent NaOH*

Component	Maximum rate	Temperature of initiation (T_i)	Residue at 450° C.
	mg./°C.	*°C.*	*Percent*
Cellulose	0.25	320	6
Cellulose + 5 percent $ZnCl_2$	.05	220	38
Cellulose + 5 percent NaOH	.04	227	40

[1]Organic basis.

The pyrolysis products from cottonwood cellulose and xylan, with and without treatment, were identified using pyrolysis GLC. To analyze the volatiles, about 12 to 20 mg. of the powdered samples were placed in a small aluminum boat and pyrolyzed at 600° C. in a Perkin Elmer pyrolysis unit connected to a Hewlett Packard F and M Model 5750 temperature programed, dual column GLC.

The connections were modified to allow the carrier gas to either bypass the pyrolysis unit or sweep the pyrolysis products directly into the GLC unit. The volatile pyrolysis products were resolved by using essentially the previously reported conditions with minor modifications (Schwenker and Beck 1963).

The columns consisted of 12 feet of 1/4-inch diameter stainless steel packed with Fluoropak 80, coated with 10 percent of 20M carbowax. The carrier gas was helium flowing at the rate of 45 ml./minute for the thermal conductivity measurements and nitrogen flowing at the rate of 60 ml./minute for flame ionization. The column temperature was programed between 50° and 210° C. at the rate of 2° to 8° C./minute. The flame ionization detector was sufficiently sensitive so that a 20:1 splitter could be used for collecting a major portion of the individual peaks for chemical identifications. The following methods were used for this purpose: (1) comparison of R_f values and spiking with known compounds; (2) mass spectroscopy of the side stream collected in a capillary tube cooled with liquid nitrogen; (3) u.v. spectroscopy of the collected material; (4) bubbling of the side stream in a solution 2,4-dinitrophenylhydrazone (DNPH) to form derivatives; (5) thin-layer chromatography (TLC) of the DNPH compounds (Byrne, Gardiner, and Holmes 1966); (6) m.p. of the DNPH derivatives; (7) i.r. spectrum of these materials; (8) Schiff's color test for aldehydes; (9) oxidation of an alcohol with $KMnO_4$ and TLC of the DNPH derivative of the resulting aldehyde; and (10) pH test for acids.

The GLC detectors were directly connected to a recorder and a Varian model 475 digital integrator. The integrator was calibrated by injecting known quantities of each compound. Carbon dioxide was identified by the precipitation of $BaCO_3$ from a $Ba(OH)_2$ solution and quantitatively analyzed by titration with oxalic acid. Water was quantitatively analyzed with GLC using the thermal conductivity detector. The charred residue left after 20 minutes at 600° C. was weighed in the original aluminum boats.

A general consideration of the items listed in table 4 indicates two types of products. One results from the fragmentation of the glucose units such as acetaldehyde, glyoxal, 1-hydroxy-2-propanone, and acrolein. The other is the type of material that can be formed from the dehydration reactions such as water, char, and furan compounds. Both of these reactions probably operate in untreated cellulose, although the degradation apparently dominates, especially at the elevated temperatures. The effect of $ZnCl_2$ treatment was to increase the amount of furan compounds, water, and char. The NaOH treatment increased the 2 and 3 carbon carbonyl compounds as well as the char (figs. 7 and 8).

Table 4.--*Pyrolysis products from cellulose (percent of original organic)*

Peak No.	Compound	Cellulose	Cellulose +$ZnCl_2$	Cellulose +NaOH	I.O. ident. method[1]
		Counts per mg.[2]			
1,2	Fixed gas	12,900	[illegible]	[illegible]	
		Percent			
3	Acetaldehyde	1.3	1.0	3.1	1,5,6,7 8
4	Acetone/propionaldehyde	[illegible]	.2	T	[illegible]
5	Furan	1.4	3.2	.8	1
6	Acrolein	1.5	T	3.1	1,9
7	Methanol	.8	.5	.6	1,5,6,9
8	Methyl furan	T	2.1	T	1
10	2,3-Butanedione	1.4	1.2	2.4	1,4,5,8
11	2-Butenal	.8	2.1	1.9	1,4,5,6 8
13	2-Oxypropanal	T	.8	T	1,5
15	1-Hydroxy-2-propanone	1.9	.3	1.4	1,5
16	Glyoxal	2.0	.1	6.9	1,5,6
17	Acetic acid	.8	.8	3.5	1,2,10
18	2-Furaldehyde	.9	2.1	1.0	1,2,3,4 5,6
19	Formic acid	T	T	1.7	1,10
20	5-Methyl-2-furaldehyde	.5	.3	.3	1,5
21	Furfuryl alcohol	.3	.3	.1	[illegible]
	H_2O	11	16	12	
	CO_2	6	4	8	
	Char	5	[illegible]	18	

[1]Refer to methods on page 12.
[2]Counts per mg. at attenuation 10^3-16.
[3]T = <0.1 percent

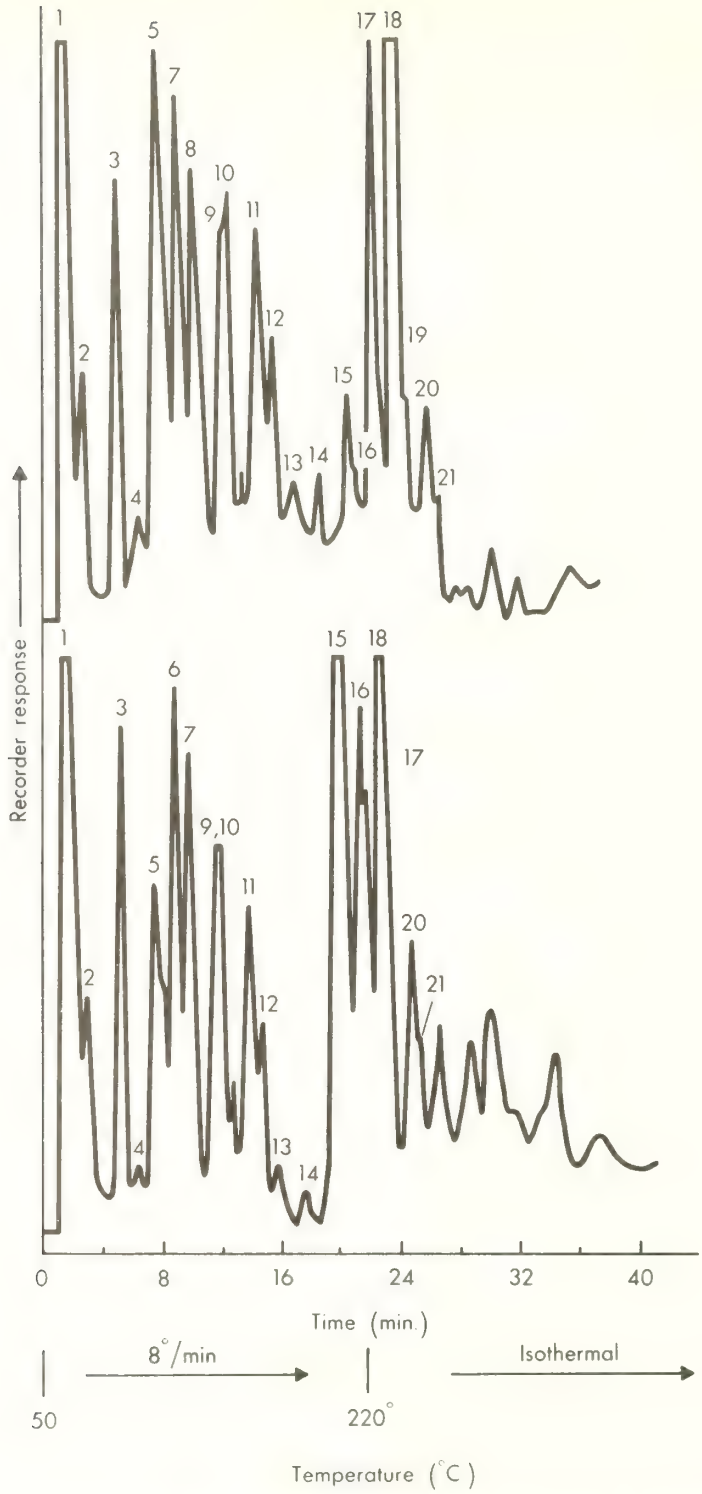


Figure 7.--Chromatogram of the pyrolysis products of cellulose (lower) and cellulose treated with 5 percent zinc chloride. The peaks are (1), (2) fixed gases; (3) acetaldehyde; (4) acetone/propionaldehyde; (5) furan; (6) acrolein; (7) methanol; (8) methyl furan; (10) 2,3-butanedione; (11) 2-oxypropanal; (15) 1-hydroxy-2-propanone; (16) glyoxal; (17) acetic acid; (18) 2-furaldehyde; (19) formic acid; (20) 5-methyl-2-furaldehyde; and (21) furfuryl alcohol.

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1971. The pyrolysis products and thermal characteristics of cottonwood and its components, USDA Forest Serv. Res. Pap. INT-107, 31 p., illus.

This study was undertaken to determine the thermal properties of, and the pyrolysis products from, western cottonwood (*Populus trichocarpa*) and two of its major components: cellulose and xylan. The modifications due to treatment of the wood and its components with an acid and alkali were also documented. Differential thermal analysis (DTA) and thermogravimetric analysis (TGA), as well as direct pyrolysis into a temperature-programed gas-liquid chromatograph, were used in this investigation.

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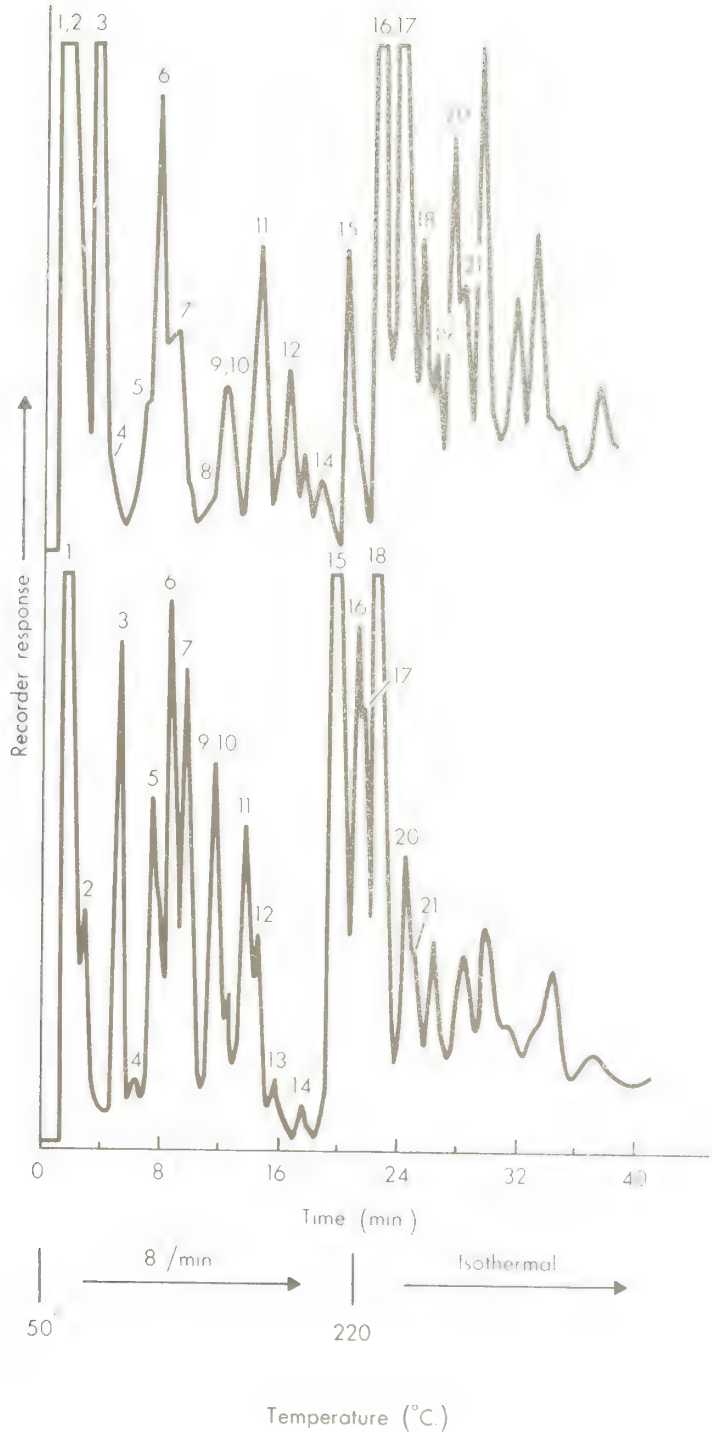

Figure 8.--Chromatogram of cellulose treated with 5 percent sodium hydroxide (see figure 7 for identification of peaks).

PYROLYSIS OF XYLAN

The hemicellulose fraction of cottonwood is mainly O-acetyl-4-O-methylglucuronoxylan (i.e., xylan). The isolation of the polysaccharide was described in a previous section. The pyrolysis studies in the past have mainly dealt with cellulose and there is little thermal degradation data on xylan. Beall[9] has reported a thermal analysis study (TGA and DTA) of hemicelluloses from different species of wood, without inorganic chemical analysis of samples. The early investigation of the products formed from xylan pyrolysis has been limited to identification of a few major compounds, especially furfural (2-furaldehyde) (Heuser and Scherer 1923).

A recent report deals with the thermal analysis of xylan isolated from beechwood, and includes a complete chemical analysis of the substrate (Shimizu, Teratani, and Miyazaki 1968). This study showed that pyrolysis of xylan takes place at about 215° C. when the polysaccharide structure disappears, as shown by IR spectroscopy. When xylan was heated further to 290° C., fragmentation of the compound occurred. Shimizu and coworkers also claimed that some polymerization, evidenced by the appearance of xylobiose above 275° C., could take place. The fragmentation and polymerization gave a net exothermic reaction which was not resolved. Maximum weight loss occurred between 215° and 290° C.

Further studies by McGinnis[10] have shown that the initial pyrolytic reaction involves breaking of the β 1→4 glycosidic bond through a carbonium ion mechanism. This conclusion is mainly based on investigation of methyl, and substituted phenyl β-D-xylosides, used as model compounds for xylan. The nature of the aglycone for these xylosides provided a wide range of glycosidic bonds. By subjecting the models to DTA and TGA, it was shown that the thermal stability of the glycosidic bonds was determined by the electron withdrawing power of the aglycone. Analysis of the products showed that the aglycone could be recovered quantitatively and therefore the 1→4 glycosidic bond must have been broken during the initial stage of the reaction.

Two kinds of xylan were described previously: the DMSO-extracted xylan which remains acetylated as in the native form, and the base-extracted xylan which has been deacetylated by the alkali. In this part of the program, both types of treated and untreated xylan were subjected to DTA and TGA as well as pyrolysis gas chromatography.

Thermal analysis of both types of xylan showed very little difference between them. The TGA (fig. 9) shows that pyrolysis began at 215° C. as indicated by weight loss and proceeded rapidly up to 275° C. The maximum rate of pyrolysis was 0.11 mg./°C. and a residue of 6 percent remained at 450° C. (table 5).

In the DTA curve there was an endotherm at the onset of rapid weight loss. This was followed by a sharp exotherm (fig. 10). Figures 9 and 10 show the effects of 5 percent $ZnCl_2$ on the TGA and DTA of base-extracted xylan. On TGA, weight loss began at 175° C. as compared to 215° C. for the untreated. The maximum rate of weight loss was 0.06 mg./°C. and a residue of 2 to 5 percent remained at 450° C. On DTA, the endotherm corresponding with rapid weight loss occurred from 175° to 225° C. and was followed by a broad exothermic region (fig. 10).

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[9] Beall, op. cit.
[10] McGinnis, op. cit.

Table 5.--*Some thermal characteristics of DMSO and base xylan treated with 5 percent [illegible] and 9 percent [illegible]*

Component	Maximum rate (R)	T_i	Residue[1]
	mg./°C.		*Percent 450° C.*
Base xylan	0.11	215	6
DMSO xylan	.11	215	6
Base xylan + 5 percent $ZnCl_2$	.06	175	25
DMSO xylan + 5 percent $ZnCl_2$	.06	175	25
Base xylan + 9 percent NaOH	.07	200	27
DMSO xylan + 9 percent NaOH	.06	200	31

[1]Organic base.

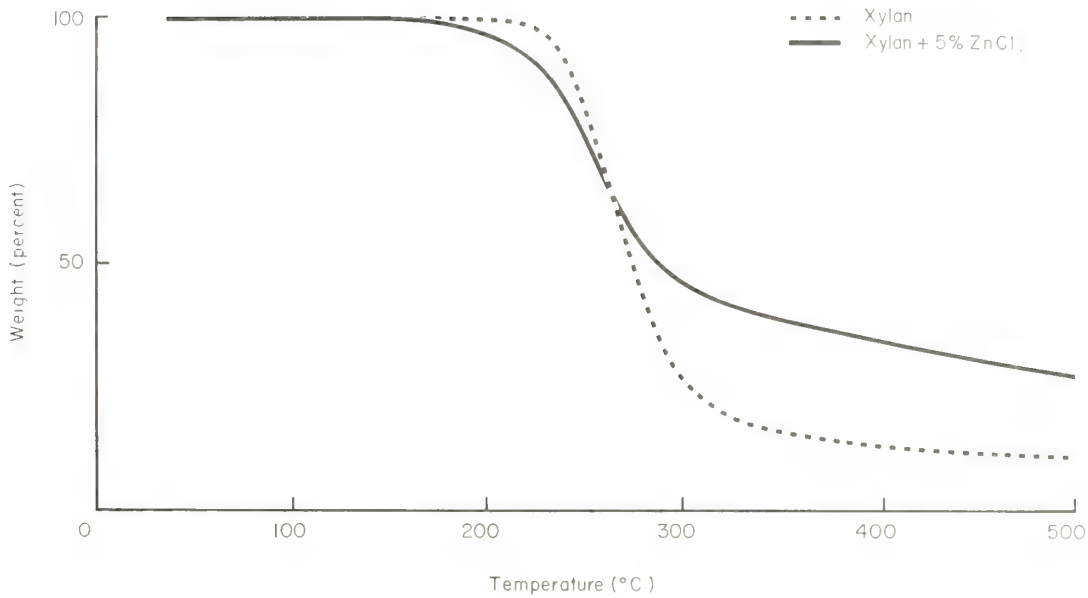


Figure 9.--Thermogravimetric analysis of DMSO xylan and DMSO xylan treated with 5 percent zinc chloride.

Figure 10.--Differential thermal analysis of DMSO xylan and DMSO xylan treated with 5 percent zinc chloride.

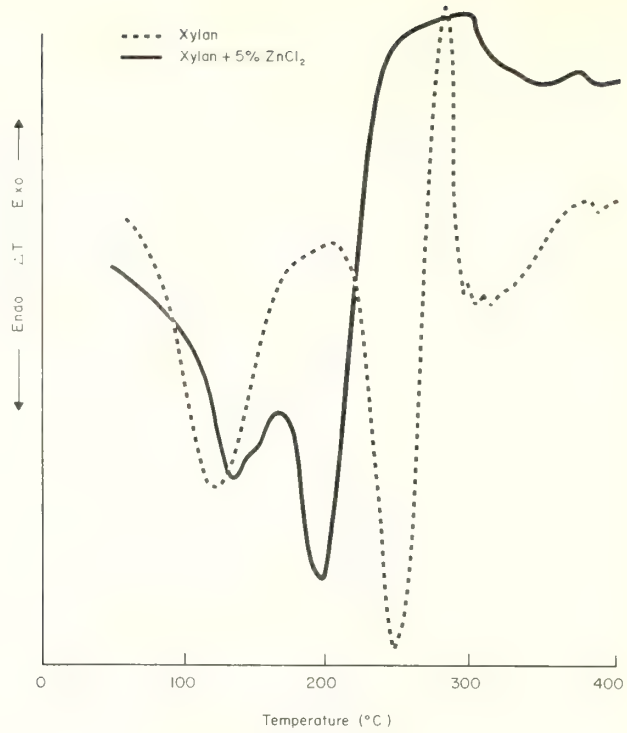


Figure 11.--Thermogravimetric analysis of DMSO xylan (II), and base xylan (I), treated with 9 percent sodium hydroxide.

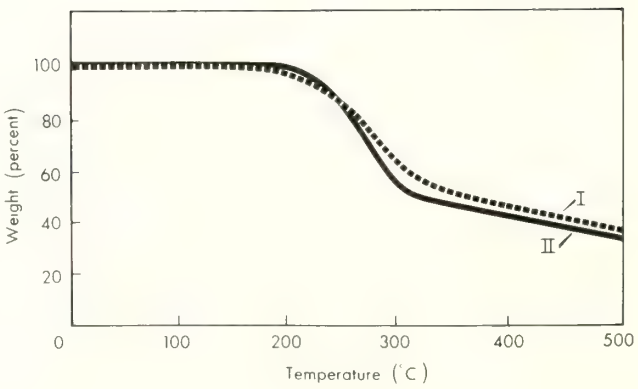


Figure 12.--Differential thermal analysis of DMSO xylan treated with 9 percent sodium hydroxide.

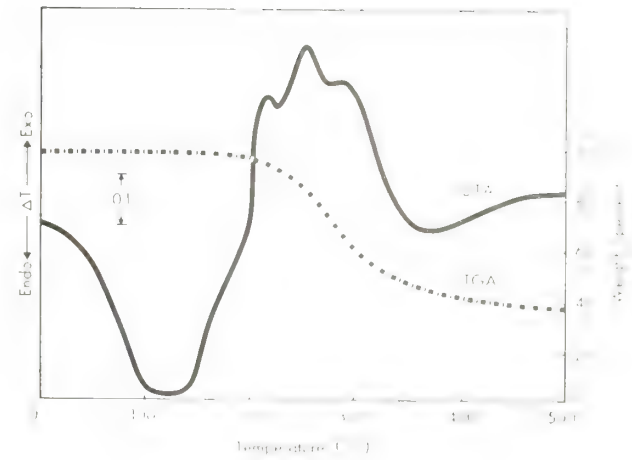
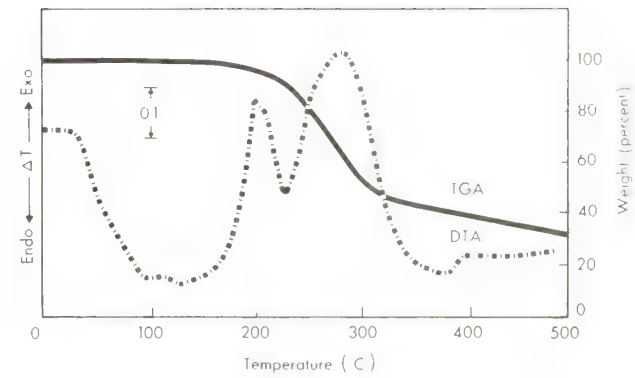


Figure 13.--Differential thermal analysis of base xylan treated with 9 percent sodium hydroxide.



The untreated DMSO- and base-extracted xylans behaved quite similarly in a thermal environment; however, the two types of xylan showed major differences when treated with alkali. Thermal analysis and pyrolysis gas chromatography showed that xylan treated at the 5 percent level of NaOH was quite similar to that which was untreated. Apparently the glucuronic acid component of the xylan neutralized about 4/5 of the alkali so the treatment was increased from 5 to 9 percent. The TGA of DMSO- and base-extracted xylan treated with 9 percent NaOH is shown in figure 11. The DMSO-extracted xylan had a higher residue and a slower rate of pyrolysis. This may be due to the greater neutralizing effect of the base-extracted xylan because there are more glucuronic acid units present per unit weight.

Figure 12 shows the TGA and DTA of DMSO-extracted xylan treated with 9 percent NaOH. The onset of rapid weight loss on TGA showed active pyrolysis to begin at 200° C. The maximum rate of pyrolysis was 0.06 mg./°C. and the residue at 450° C. was 31 percent. There was a net exotherm from 200° to 325° C. during rapid weight loss shown on DTA (fig. 12). The DTA of base-extracted xylan treated with 9 percent NaOH showed an endotherm at the onset of rapid weight loss and a subsequent exotherm from 225° to 325° C. (fig. 13). The maximum weight loss rate was 0.07 mg./°C. and the residue at 450° C. was 27 percent.

Neat DMSO- and base-extracted xylan were pyrolyzed and the products swept directly into the GLC. The major products were identified by the previously described methods (table 6, fig. 14). As expected, much more 2-furaldehyde was produced from xylan as compared to cellulose. The large amount of acetic acid from DMSO-extracted xylan was quantitatively equal to the acetate groups, plus what was produced from the deacetylated product. However, the DMSO-extracted xylan produced twice as much H_2O, half as much acetaldehyde and 2-furaldehyde, and some other differences that could not be readily explained.

The two types of xylan were treated with the additives so that the pyrolysis products could be identified, quantified, and compared to those of treated cellulose and wood. Treatment of both xylans with 5 percent $ZnCl_2$ had an effect similar to that found for treated cellulose (fig. 14). There was an increase in furan compounds and a decrease in 2 and 3 carbon carbonyl compounds (table 6). However, the acetaldehyde produced from the $ZnCl_2$ treated DMSO-extracted xylan was about twice that of the untreated DMSO-extracted xylan. The 2-furaldehyde was increased by 2.2 times for both types of xylan treated with 5 percent $ZnCl_2$, although there was still twice as much 2-furaldehyde produced from the base-extracted xylan.

The effects of 9 percent treatment on both types of xylans also produced results (table 6) generally similar to alkali-treated cellulose (fig. 15). The small carbonyl compounds increased and the furan compound decreased. The compounds showing the greatest increase were acetone, propionaldehyde, and crotonaldehyde. There was also an increase in CO_2 and H_2O.

Table 6.--*Pyrolysis products from xylan (percent of organic volatiles)*

Peak no.	Compound	Neat		5% $ZnCl_2$		2% KOH	
		DMSO	Base	DMSO	Base	DMSO	Base
		Counts per mg.[1]					
1,2	Fixed gases	18,100	20,400	5,500	5,000	19,400	14,800
		Percent					
3	Acetaldehyde	1.0	2.4	1.9	.1	1.6	1.6
4	Furan	2.2	T[2]	3.5	2.0	.4	.3
5	Acetone	1.4	0.3	T	T	5.8	3.3
6	Propionaldehyde			T	T		.7
7	Methanol	1.0	1.3	1.0	1.0	1.8	2.1
11	2,3-Butanedione	T	T	T	T	T	T
12	Ethanol	T	T	--	--	.6	.6
13	Crotonaldehyde	T	T	--	--	1.4	1.2
14	1-Hydroxy-2-propanone	.5	.4	T	T	.8	2.0
15	Acetoin	.6	.6	T	T	.6	
16	Acetic acid	10.3	1.5	9.3	T	3.4	3.1
17	2-Furaldehyde	2.2	4.5	5.0	10.4	.6	1.6
	Char	10	10	23	26	23	21
	CO_2	8	8	6	7	22	14
	H_2O	14	7	15	21	19	26

[1]Counts per mg. at attenuation 10^3-32.
[2]Less than 0.1 percent.

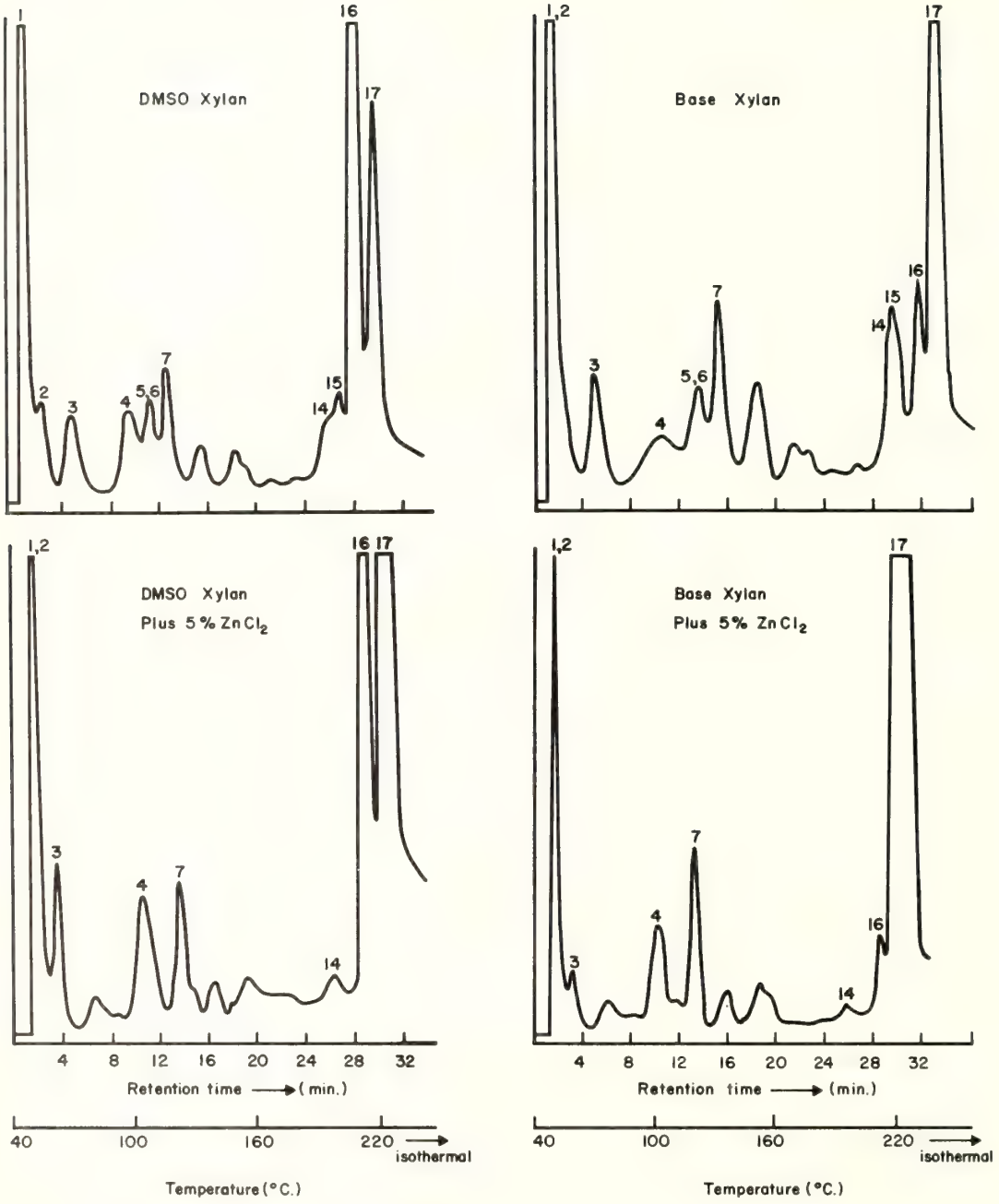


Figure 14.--Chromatograms of DMSO and base xylan with and without treatment with 5 percent zinc chloride. The peaks are: (1), (2) fixed gases; (3) acetaldehyde; (4) furan; (5) acetone; (6) propionaldehyde; (7) methanol; (11) 2,3-butanedione; (12) ethanol; (13) crotonaldehyde; (14) 1-hydroxy-2-propanone; (15) acrolein; (16) acetic acid; and (17) 2-furaldehyde.

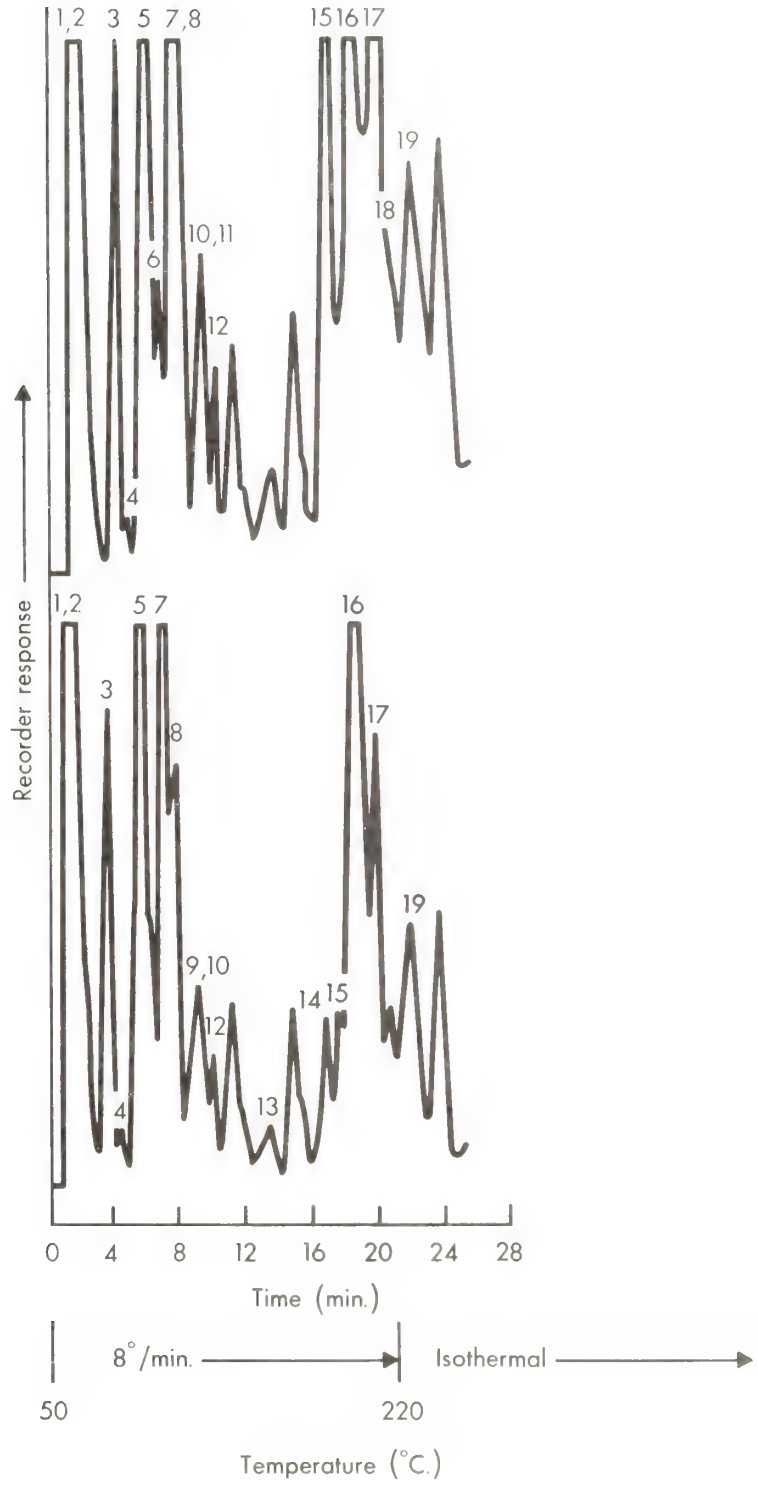


Figure 15.--Chromatograms of DMSO and base xylan treated with 9 percent sodium hydroxide (see figure 14 for peak identification).

PYROLYSIS OF COTTONWOOD

One of the goals of this study was to investigate the pyrolysis of whole wood and its major components with and without the presence of additives. In order to carry this out, cottonwood was studied by TGA, DTA, and pyrolysis GLC, using the methods previously described. The thermal analysis of untreated cottonwood was presented in a previous section. The pyrolysis products from untreated cottonwood, cottonwood treated with 5 percent $ZnCl_2$, or 5 percent NaOH, as well as the TGA and DTA of treated wood, will be presented in this section. Since lignin complicates the study of wood, some work with this component was necessary. The TGA of lignin has been previously presented and a limited amount of pyrolysis GLC data is discussed here. As previously noted, the thermogram of cottonwood is quite complex. Pyrolysis of each component can be identified by its characteristic thermal behavior and the thermogram of the whole wood is a composite of the thermal behavior of all of the components.

Treatment of cottonwood with 5 percent $ZnCl_2$, which can be observed by DTA (fig. 16), shows the effect of this additive on each component. The xylan endotherm beginning at 175° C. and the cellulose endotherm beginning at 240° C. were both present. However, the net endotherm from cellulose was greatly reduced by the exotherm of xylan from 250° to 300° C. The TGA also appears to be a composite of the pyrolysis behavior of the components. Table 7 shows computations which account for the char from TGA of wood and its components, assuming no effect of $ZnCl_2$ or NaOH on the amount of lignin char.

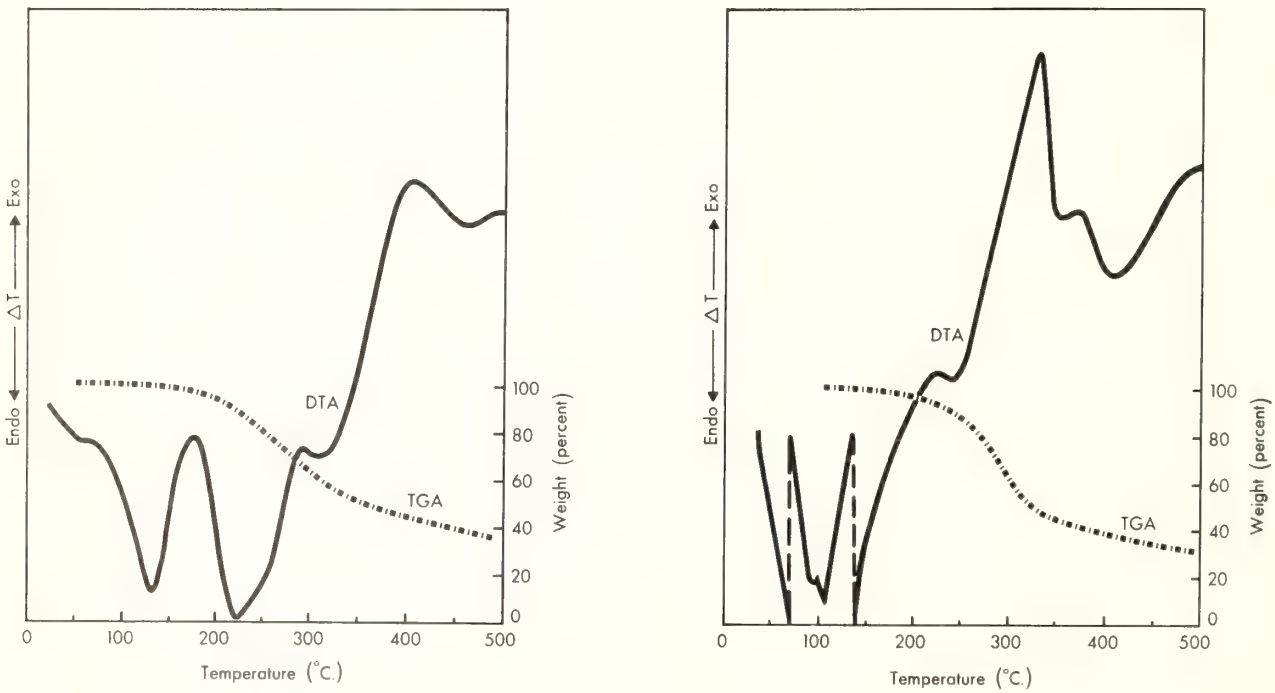


Figure 16.--(Left) Thermogram of cottonwood treated with 5 percent zinc chloride. (Right) Thermogram of cottonwood treated with 5 percent sodium hydroxide.

Table 7.--*Comparison of char from cottonwood and its components*

Component	Composition percent	Char formed (percent)					
		Neat		[illegible]		NaOH	
		A[1]	B[2]	A	B	A	B
Cellulose	44	6	2.6	[illegible]	14.5	22	9.7
Xylan	21	6	1.3	27	5.7	31	6.5
Milled wood lignin	32	45	14.4	45	14.4	45	14.4
Sum of char from components			18.3		34.6		30.6
Actual organic char from wood			19.0		35.0		30.0
Difference			-.7		-.4		.6
Error (percent)			3.7		1.1		2.0

[1] Residue at 450° C. from TGA minus treatment in percent.
[2] Net char at 450° C. X percent the component makes up of whole wood.

The effects of 5 percent NaOH on the pyrolysis of cottonwood can be seen on DTA as being generally made up of the combined effect of alkali on cellulose and xylan. The net process was exothermic after water loss (fig. 16). A slight dip occurred in the DTA trace at about 240° C. and corresponds to the endotherm at that temperature on the DTA of cellulose treated with alkali (fig. 6). The TGA shows a char which was equal to the weighted chars from the alkali treated components (table 7).

The volatile products from the pyrolysis of wood were qualified and quantified using previously described methods. Milled wood lignin was studied by pyrolysis gas chromatography so that any major peaks from this component could be identified on the chromatogram of wood.

The pyrolysis of milled wood lignin gave four major peaks on the chromatogram (fig. 17). In addition to fixed gases, these peaks appeared to be methanol (L_1), acetic acid (L_2), and the largest peak, (L_3), which is unidentified. Kitao and Watanabe (1967) identified several products from the pyrolysis of beech milled wood lignin. Three major peaks, presumably of low molecular weight, were not identified in the paper, but they could certainly be methanol, ethanal, and acetic acid. The products they did identify formed relatively minor peaks except for a combined peak of tranisoeugenol and pyrogallol-1, 3-dimethylether. Possibly this is the major peak labeled L_3 on the chromatograms, but, due to differences in columns and wood species, little can be said concerning the identity of the peak. It should be noted that the same peak, (L_3), appears in all the chromatograms of wood and is greatly reduced by $ZnCl_2$ treatment (figs. 17 and 18). The possibility of using this pyrolysis procedure to quantify lignin content should be investigated to see if this time-consuming procedure could be automated.

Figure 17.--(Upper) Chromatogram of cottonwood (see figure 7 for peak identification). (Lower) Chromatogram of milled wood lignin (see text for description).

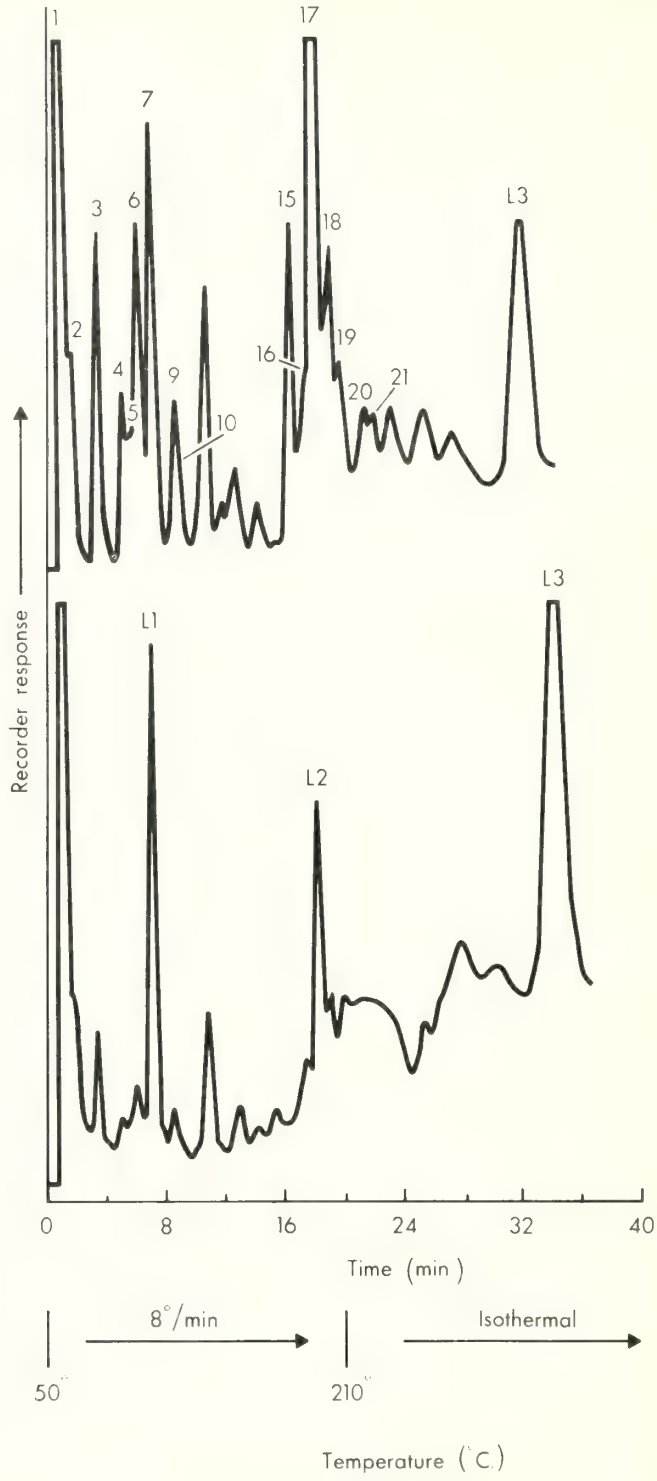
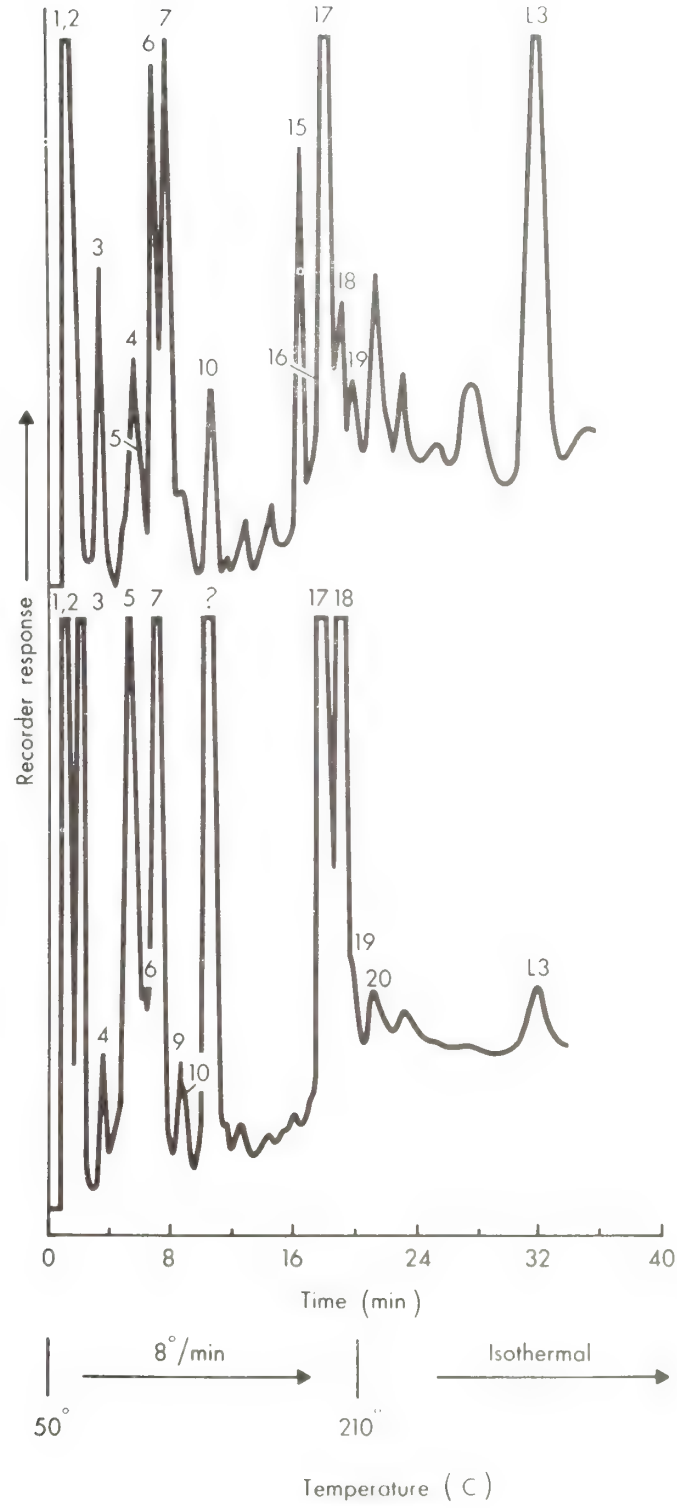


Figure 18.--Chromatogram of cottonwood treated with 5 percent sodium hydroxide (upper) and 5 percent zinc chloride (lower) (see figure 7 for peak identification).



The chromatogram from the pyrolysis of cottonwood is shown in figure 17. These products are quantified in table 8. Additional compounds identified for both cellulose and cottonwood were levulenic acid (retention time) and 5-(hydroxymethyl)-2-furaldehyde (retention time and TLC). All of the major peaks can be identified from the chromatograms of cellulose, xylan, and lignin.

The chromatogram of cottonwood treated with 5 percent $ZnCl_2$ is shown in figure 18. The products are quantified in table 8. Generally, the effect of $ZnCl_2$ was similar to that which occurred when the same treatment was given xylan and cellulose. With the exception of acetaldehyde, furan compounds increased and 2-3 carbon compounds decreased. The peak identified by a question mark in figure 18 was also greatly increased by the $ZnCl_2$ treatment; this peak was probably due to the effect of the treatment on lignin. Until lignin is more completely investigated, extrapolation of the volatiles produced from the components to the whole wood will be difficult.

Treatment of wood with 5 percent NaOH increased the production of 2 and 3 carbon fragments. This is similar to what occurred when cellulose and xylan were treated with alkali (fig. 18). However, there was no reduction in the amount of furan compounds produced from untreated wood.

Table 8.--*Pyrolysis products from wood*

Peak no.	Compound	Amount			
		Wood	+$ZnCl_2$	+NaOH	I.D.
		Counts per mg.			
1,2	Fixed gases	21,900	9,100	31,800	
		Percent			
3	Acetaldehyde	2.3	4.4	3.4	1,5,6,7,8
4	Acetone/propionaldehyde	1.5	.9	3.2	1,5
5	Furan	1.6	7.9	1.7	1
6	Acrolein	3.2	.9	4.8	1,9
7	Methanol	2.1	2.7	5.7	1,5,6,9
8	Methyl furan	*[1]	*	*	1
10	2,3-Butanedione	2.0	1.0	5.6	1,4,5,8
15	1-Hydroxy-2-propanone	2.1	T[2]	3.4	1,5
16	Glyoxal	2.2	T	1.5	1,5,6
17	Acetic acid	6.7	5.4	7.3	1,2,10
18	2-Furaldehyde	1.1	5.2	1.0	1,2,3,4,5,6
19	Formic acid	.9	.5	1.6	1,10
20	5-Methyl-2-furaldehyde	.7	.9	1.0	1,5
21	Furfuryl alcohol	.5	T	.8	1
	CO_2	12.1	6.0	13.8	
	H_2O	18.0	18.4	20.1	
	Char	15.0	24.0	30.0	

[1] * = not clearly identifiable for wood.
[2] T = approximately 0.1 percent.

SUMMARY AND CONCLUSIONS

The major conclusions from this study are:

1. The major component of western cottonwood hemicellulose is 0-acetyl-4-0-methyl glucuronoxylan (xylan), making up about 95 percent of the noncellulose carbohydrate.

2. The three major components of western cottonwood, cellulose, xylan, and lignin have quite dissimilar thermograms, but all three are reflected in the thermogram of the whole wood. This independent behavior makes it quite likely that each component can be studied independently and the results used to predict its behavior within whole wood. This greatly simplifies the study of the complicated pyrolysis of wood.

3. The hemicellulose 0-acetyl-4-0-methyl glucuronoxylan is almost completely pyrolyzed prior to the beginning of cellulose pyrolysis. This makes the hemicellulose component more important to the fire problem than generally thought, especially since the pilot ignition temperature is around 300° to 340° C.

4. Lignin is the least important component in the pyrolysis of wood because of its products, rate of decomposition, and high yield of char. Since the char probably contributes mainly to glowing, lignin may be quite important to the hold-over fire in punk or decomposed plant material.

5. Contrary to past work (Schwenker and Beck 1963), no formaldehyde from the pyrolysis of these carbohydrates was found. This agrees with Wodley (1969).

6. Cellulose, xylan, and wood all exhibit dissimilar thermograms and volatile products between zinc chloride and sodium hydroxide treatment. The zinc chloride produces more of the furan compounds, especially 2-furaldehyde, and a decrease in 2 and 3 carbon compounds. The sodium hydroxide decreases the furan compound and increase 2 and 3 carbon compounds. Obviously these two model retardants are acting by dissimila mechanisms.

7. Zinc chloride and sodium hydroxide both cause an increase in char and water production. This probably means they both lead to more glowing combustion than would occur with the untreated fuel. However, any flame retarding effect is due to a combination of decreases in volatilization amount and rate as well as increases in water and char production. Since these two compounds act differently, each effect must be weighted accordingly.

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Logan, Utah (in cooperation with Utah State University)
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Stratification of Forest Land for Timber Management Planning on the Western National Forests

J. H. Wikstrom and S. Blair Hutchison

USDA Forest Service Research Paper INT-108, 1971
INTERMOUNTAIN FOREST AND RANGE
EXPERIMENT STATION
Ogden, Utah 84401

UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE

INT Ogden

REPLY TO: 4820 Production Economics October 29, 1971

SUBJECT: Forest Land Stratification Study

TO: Chief

Enclosed is a report of the study, Forest Land Stratification for Timber Management Planning on the National Forests of the West, that you requested the Intermountain Station and six Western Forest Service Regions to undertake cooperatively. Although we have no basis for saying the data presented in this report represent a statistical average for the western National Forests, they do indicate the general nature of the situation.

This study concludes work initiated in response to Recommendation No. 4 of the 1966 General Integrating Inspection of the Northern Region and the Intermountain Station. We have had the full cooperation of the Regional Forester and staff of each of the six Western Regions in carrying out this study. It is, therefore, with great satisfaction that I submit this report to you on behalf of the Station and the cooperating Regions.

Robert W. Harris

ROBERT W. HARRIS
Director

Enclosure

COVER PHOTO: A 17-year-old stand of lodgepole pine on the Gallatin National Forest, Montana. The stand was thinned in 1962.

USDA Forest Service
Research Paper INT-108
October 1971

Stratification of Forest Land for Timber Management Planning on the Western National Forests

J. H. Wikstrom and S. Blair Hutchison

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U. S. Department of Agriculture
Ogden, Utah 84401
Robert W. Harris, Director

ABSTRACT

The area of forest land now considered suitable and available for sustained timber management on six western National Forests is about one-fifth less than previously reported. The reduced area is not greatly different from the area used as a basis for allowable cut calculations.

The reduction in area estimates reflects more precise consideration of land productivity, land instability, isolation of small stringers and patches of forest land, and impacts of improved multiple use planning. Revised classifications of forest land in terms of planned use contributed most to the reduction of areas classed as commercial forest land. This in turn largely reflects an improved data base and procedures for multiple use planning.

Adequate information is not available to determine how much the reduction of the timber growing base area will reduce the allowable cut of timber on the six Forests studied. However, the impact on allowable cut will be less than the reduction in area. On many Forests, adjustments have been made for various constraints on timber harvesting and allowable cut estimates have been calculated for only the more accessible and productive forest areas.

This study emphasizes the need for resource inventory work that will describe and update timber and other resources in relation to the land, land-use status, and other factors that affect forest development and use. Timber and other resource inventories must be coordinated and related to land characteristics and other current factors that are significant in the multiple use management of these public forest lands.

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Introduction

Between 1952 and 1969, total timber harvested in the West showed an increase of 35 percent. In this same period, timber cutting on the National Forests of the West showed a dramatic 154 percent increase, from 3,855 million board feet to 9,798 million. From a significant, but somewhat secondary place in the Western timber supply picture, the National Forests have moved to a dominant role.

As long as the level of timber harvested on National Forests was relatively low, the question of how much wood the Forests could produce within a program of sustained yield was neither immediate nor critical. However, as the rate of cutting has increased, the question of upper limits of cut has become a current issue — often a crucial one. This question has become especially critical on those National Forests where increasing the annual cut means harvesting timber in more difficult areas of terrain, the capabilities of which are yet to be adequately determined. These areas tend to be physically and biologically more complex and much more information about them is required to plan acceptable usage of them.

Even under the best circumstances this question of proper cutting levels would be hard to answer; and it has now been greatly aggravated by the increase of other demands on the Forest. Today, more watershed protection is required, recreation use is mounting, and there is greater interest than ever before in maintaining scenic quality, fish and wildlife habitat, and other values. It is apparent that all of these other requirements of management are going to have a greater impact on timber yields — at least in the next few decades — than had formerly been anticipated.

In recent months the allowable cut estimates on some National Forests have been reduced because of second thoughts about the size of the harvest that could be sustained. On other National Forests there has been public clamor to reduce cutting levels which are alleged to be too high for sustained yield. There are counterclaims, of course, that National Forest harvest levels are quite reasonable. Certainly on many Forests if more intensive management were applied, the cut could be substantially increased in time.

Throughout this report we have used the term "timber growing base" when referring to forest land suitable and available for timber growing. To many this term "timber growing base" is synonymous with "commercial forest land" and even the standard Forest Survey definition of "commercial forest land" is forest land suitable and available for timber growing. However, in some circles "commercial forest land" includes any forest land from which timber may be cut. Therefore, since this study is concerned with identification of only the forest land suitable and available for timber growing, the term "timber growing base" is used to avoid confusion.

Since allowable cut levels and management plans are functions of the assumptions underlying them, the principal effort of this study has been directed to reexamining the stated and implicit assumptions with regard to forest land stratification on the National Forests. The procedures for implementing the assumptions have also been examined.

The most recent timber growing statistics for the West (excluding Alaska and Hawaii) reveal that there are 109 million acres of forest

land in National Forests. Of this total, 71 million acres have been classed as "commercial;" that is, *the timber growing base.*

In this report we will answer the following questions:

- HAS THE TIMBER GROWING BASE BEEN PROPERLY DETERMINED? IN OTHER WORDS, HAVE ALL THE FACTORS AFFECTING THE SUITABILITY AND AVAILABILITY OF THE FOREST FOR TIMBER GROWING BEEN ADEQUATELY TAKEN INTO ACCOUNT?
- HAS THE TIMBER GROWING BASE BEEN SUBDIVIDED IN A MEANINGFUL WAY THAT REFLECTS TIMBER GROWING OPPORTUNITIES AND PROBLEMS?
- HOW CAN THE CLASSIFICATION OF FOREST LAND FOR TIMBER PRODUCTION PLANNING BE IMPROVED?

This study has been directed by the Intermountain Forest and Range Experiment Station. However, it has been a cooperative endeavor, involving National Forest and Regional Office personnel in the six Forest Service Regions headquartered at: Missoula, Montana; Denver, Colorado; Albuquerque, New Mexico; Ogden, Utah; San Francisco, California; and Portland, Oregon. Much of the work in connection with this study was done by National Forest Systems people and much of their thinking has gone into the study. The conclusions drawn in this report, however, are solely the responsibility of the Intermountain Forest and Range Experiment Station.

A word of caution! Only six National Forests, or portions thereof, were analyzed to derive study data and other information presented here.

Lolo National Forest (portion),
Arapaho National Forest,
Coconino National Forest,
Boise National Forest (portion),
Klamath National Forest — East Working Circle,
Gifford Pinchot National Forest — Gifford Pinchot Working Circle.

Selection of the six Forests was based primarily on convenience, but they presumably represent the range of variation in land and land use factors. However, collectively they may or may not represent the average situation in the West; we simply don't know. Moreover, the fact that we identify and discuss categories in this study beyond those intended in the original survey reduces the reliability of the data. They are useful only in describing the problem of forest stratification and indicating the general magnitude of the factors considered.

To recapitulate, the specific purpose of this study is to take a first step toward clarifying the issue of identifying and stratifying the timber growing base. This is an exploratory study to determine if past estimates of the timber growing base (commercial forest area) in the western National Forests are reasonably accurate. The findings on the following pages are based partly on an evaluation of physically measurable factors and partly on an appraisal of the inventory system in relation to the purposes for which the timber data are to be used.

Procedure for determining the timber base

Forest land is usually quite easily distinguished from nonforest land on aerial photographs. The usual procedure in making timber inventories is to begin with the total forested area and then identify those areas not suitable or available for timber use, using physiographic, soil, hydrologic, ecologic, and land-use information. After the forest land suitable and available for timber growing has been identified, this area must be stratified in a way that reflects degree of suitability and availability for timber production, types or kinds of management needed, and product output options.

There are some areas that are either not suitable or not available for inclusion in present timber growing plans. These areas can be divided into six general classes:[1]

(1) Forest land formally set aside for wilderness, primitive areas, etc.
(2) Forest land that does not meet minimum productivity or wood quality standards.
(3) Forest land that is too unstable or too steep to be logged without damage to environment.
(4) Forest land that occurs in small isolated patches that are not practical to utilize and which often have higher value for other purposes.
(5) Forest land administratively withdrawn from timber use in multiple use plans.
(6) Forest land being considered for wilderness or other uses that would preclude timber utilization, but for which a decision has not been made.

The underlying problem in past inventories has been the inadequacy of information about the land, its ecology, and land use. This study was conducted, therefore, only after consulting National Forest staff specialists who developed more complete information on geomorphology, ecology, and land use. This information then provided the basis for timber inventory classification. Details are discussed later in this report.

[1] *It is important to recognize the currentness of the timber growing base classification. There is nothing permanent about the decisions in forest land classification. For example, areas presently regarded as usable for timber growing may not be so regarded a decade from now, as better information about the land becomes available or because of changed land use decisions. Likewise, areas now considered unsuitable or unavailable for timber growing may later be regarded as usable.*

Overestimation of the timber growing base

Former timber inventories on the six National Forests that were analyzed indicated an aggregate timber growing base area of 4.1 million acres. However, this timber growing base is reduced to 3.2 million acres when careful account is taken of soil-slope conditions, land productivity, and land use. In other words, the area suitable and available for growing tree crops on these six National Forests is 22 percent less than had been previously estimated.

The timber growing base was not overestimated to the same degree on all of the six Forests. On the Gifford Pinchot Working Circle, the decrease is only 11 percent as compared to 40 percent decrease on the Arapaho National Forest. (Data for each of the six areas are presented elsewhere in this report.) The significant point is that, in every case, a more careful and critical look at availability, growth capacity, and land suitability (primarily stability) resulted in a significant reduction of the area deemed suitable and available for timber growing.

These reduction figures did not come as a surprise; National Forest administrators have recognized this problem for several years and have been decreasing the area figures used in calculating allowable cuts. This study is, therefore, distinguished primarily by the fact that it represents the most systematic effort to identify and measure the factors that reduce the land base for timber growing on the National Forests.

Much of the land excluded from the timber growing base by the tighter standards and more systematic classification of this study is on the lower end of the productivity scale. Thus, the 22 percent reduction in timber growing base area on the six Forests does not indicate that the timber producing capability will be reduced by that amount. Data inadequacies prevented determining the exact effect of area reductions on yield capabilities for all of the National Forests. However, on the Coconino National Forest the timber growing base area was reduced by 28 percent, but the growth capability of that National Forest was reduced only 18 percent. On the Gifford Pinchot Working Circle the decline in growth capability was 7 percent as compared with 11 percent decrease in acreage.

The factors that affect classification of the timber growing base vary so widely from place to place that few generalizations are safe. Land use considerations of one sort or another were a big item on all but one National Forest. However, land instability, low productivity, and uneconomic units are all important to different degrees on different Forests.

Following are the percentages of the total 0.9 million acres eliminated from the timber growing base of all six National Forests. Please remember that we have no basis for saying just how representative is each of these percentages. They are presented only to indicate that each factor is important.

	Percent
(1) Areas not capable of producing 20 cubic feet of wood per acre per year	20
(2) Land too unstable to be logged without serious damage and other unsuitable forest soil	19
(3) Patches of timber land too small and/or too isolated to be utilized for timber production	7
(4) Commercial quality lands administratively withdrawn from timber use in multiple use plans	35
(5) Areas under study to determine appropriate land use such as wilderness for which a final decision has not yet been made[2]	19
	100

[2] *Plans for the areas in category (5) are obviously incomplete pending a decision which will either put them in or out of the timber growing base.*

Variations within the timber growing base

On the 3.2 million acres *that comprise the timber growing base* in the six Forests there is a wide range of productivity, but there are also other differences. Some stands are less economical to develop than others due to location and type of timber. In fact, high development costs or low product values may in some cases preclude utilization in the foreseeable future. Some potentially utilizable areas can't be safely logged until systems that cope with fragile soil problems are developed. Some stands present very difficult silvicultural problems. In other cases nontimber uses and values will preclude capturing the full yield potential of the land.

Most National Forests have made some attempt to adjust their planning to these variations. The Timber Management Division of the Forest Service, Washington Office, prepared a tentative classification scheme for nationwide use in defining subcategories of the timber growing base in 1967. The important point is that on the six Forests studied a significant part of the total 3.2 million-acre timber growing base (as indicated below) is either economically or technologically unavailable at present although in the future it presumably will be usable.

	Percent
Currently usable, both economically and technologically	87
Unavailable, either economically or technologically	13
	100

Economic feasibility is almost certain to improve with time, but the technologically unavailable timber represents a more serious problem. Some of the timber in this currently unavailable 13 percent is growing on steep slopes that are unstable and should not be logged using conventional systems, but timber in this category may be obtainable in the future under the new system of logging (fig. 1). Development of economic long-reach yarding systems such as the skyline and balloon systems that require substantially fewer roads will eventually be necessary to avoid reduction of cutting levels. On a National Forest like the Boise, which has much unstable land, there is not much time remaining for achievement of such development.

Figure 1.—Aerial view showing roads built for logging on an area in northern Idaho. At present, logging technology is heavily dependent on roads. In steep country it is not uncommon to build 12 or more miles of roads per square mile of forest land harvested. The steeper, less stable slopes simply cannot stand such disturbance. The utilization of most of these areas, therefore, will depend on aerial logging systems requiring fewer roads. Some of the most unstable slopes should not be logged at all and therefore should not be part of the timber growing base.

Sources of the problem and development of more useful and realistic area data

Why has too much land been included in the timber growing base in most, if not all, western National Forests? Primarily it is because information required for a complete job of stratifying forest land has been almost totally inadequate; not enough has been known about the productivity, stability, and ecology of the land. Furthermore, land use intentions have not been as completely or specifically spelled out as they should be, and this affects inventory classification.

A longstanding problem that is only now being corrected is the deficiency of information about soil-slope characteristics and the performance of water flows on and through the soil in these various situations. Without these facts, the areas that are either too unstable to tolerate logging or require special logging methods cannot be identified and delineated.

The principal factor undermining timber inventory data has been the incompleteness of past multiple use plans. The areas to receive special management that would reduce or eliminate timber yield possibilities have not all been identified and mapped. Even where adequate mapping has been done, the constraints and broad guidelines have not in some cases been spelled out clearly enough to provide a basis for timber classification.

Each of the six Western Regions is moving rapidly in the direction of making its multiple use plans more definitive and articulate. However, before the National Forests can completely accomplish this they must have the necessary land information, ecological data, information on use demands, and a clear sense of purpose before preparing or revising multiple use plans. Only after really meaningful multiple use plans are prepared will it be possible to accurately classify land for timber management planning.

Timber area-and-volume estimates in most cases have been based on the classification and measurement of sample points and sample acres without giving particular attention to the suitability and availability of the Forest on which these samples are taken or the size of the stands represented by the samples. This has tended to adversely affect the realism of the inventory data.

More realistic stratification of the timber growing base is needed

The recent acceleration of timber cutting and management on the National Forests has created demands for timber data that describe problems, opportunities, and management needs in a meaningful way. One of the most serious weaknesses of past data was the inadequate portrayal of the varying degrees of suitability and availability of commercial forest land for timber use. Before the costs of different levels of production can be determined, it will be necessary to classify the timber growing base to reflect the degree of suitability and availability for timber growing. Each of the six Regions and the Washington Office Division of Timber Management has struggled with this problem, but there is still no overall categorization that includes all the significant factors that affect the cost of using forest land for timber production and the results expected.

Figure 2 outlines the basic classification for the timber production planning that now appears to be necessary on National Forest land. Total forest area should be subdivided into three broad classes that can in turn be subdivided as necessary.

1. *Nonproductive, nonsuitable, and withdrawn areas.* Usually this class is called "noncommercial" and would include:

   - All forest areas that lack the capacity to grow at least 20 cubic feet of timber per acre per year — 20 cubic feet being the established dividing line between "productive" and "nonproductive."
   - Productive areas that have been withdrawn from timber use in wilderness areas, primitive areas, etc.
   - Productive areas that have been withdrawn from timber use in multiple use plans.
   - Productive areas that are so steep, unstable, or rocky that they cannot be used for timber production without serious damage to land or water or other intolerable complications.

2. *Decision deferred*

   Areas for which a final decision has

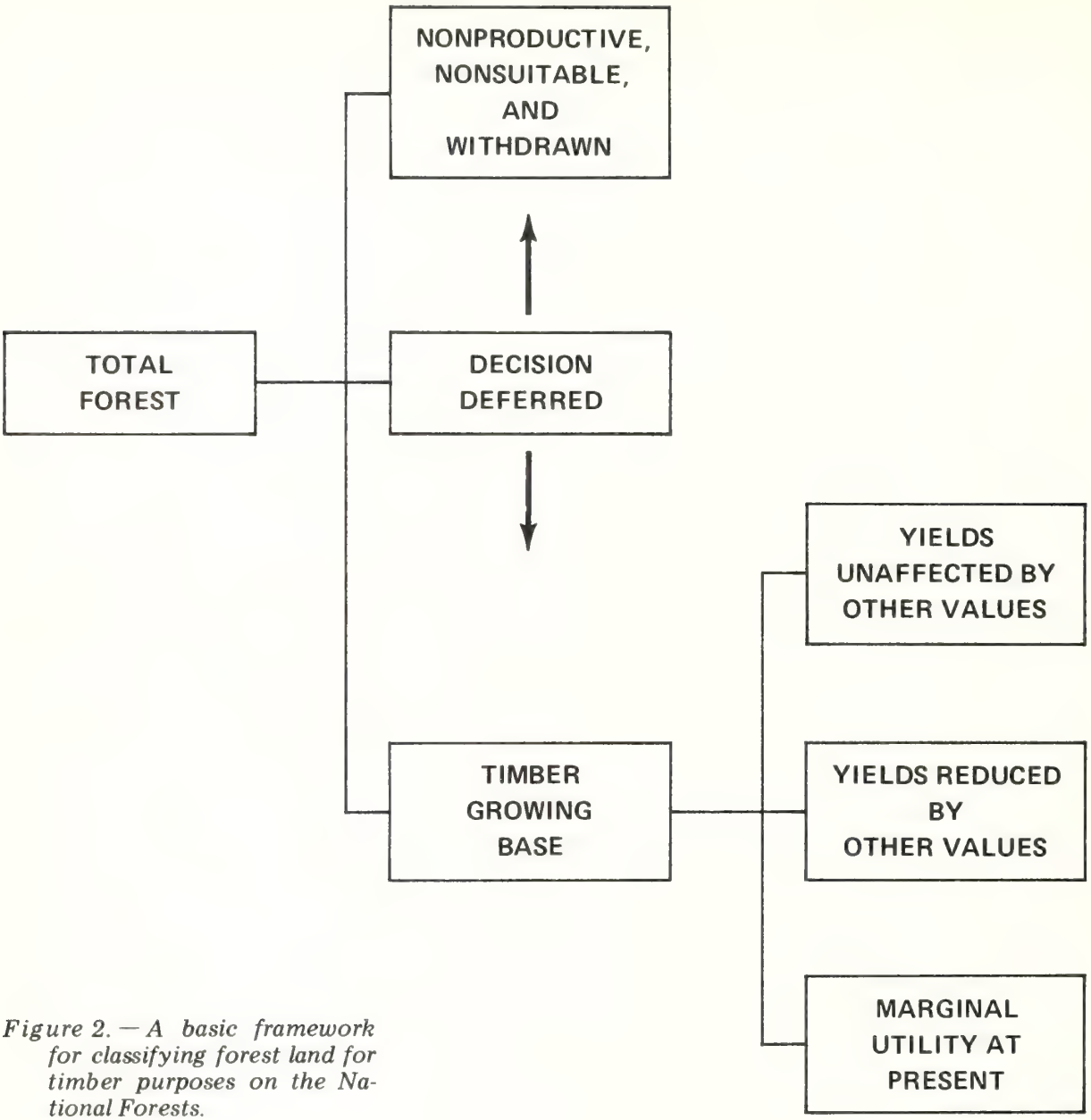

Figure 2. — A basic framework for classifying forest land for timber purposes on the National Forests.

not been made as to management purpose and on which roadbuilding, logging, and other activities associated with timber use would reduce the options for later choice. Included in this category would be areas under consideration for wilderness and any other uses with which timber cutting and timber growing would be in conflict.

3. *Timber growing base*

Productive areas that are suitable for timber use that have not been temporarily or permanently withdrawn from such use. In addition to describing such areas as to forest type, timber size, and productivity, three other broad subdivisions are needed. These follow:

(a) *Yields unaffected by other values*

Areas suitable and available for timber growing that presently can be used for this purpose without a significant reduction of timber yields.

(b) *Yields reduced by other values*

Areas presently suitable and available for timber production on which protecting or enhancing of other values such as recreation, esthetics, and watershed protection will result in reduced timber yields.

(c) *Marginal utility at present*

To avoid the possibility of overcutting, certain areas of the timber growing base are not included in the calculation of current cutting budgets because the current utility of these areas is shadowed by limitations or restrictions. These "marginal" areas include the following:

- Areas where there is low probability of the timber being utilized in the immediate future because of excessive development costs or low timber-product values.
- Unstable land areas that cannot be logged using present methods without damaging the environment but which may be utilized for timber once a logging system is developed that will not damage the environment.
- Merchantable stands on sites where reforestation following logging would be extremely difficult or expensive because of adverse site and/or habitat conditions.
- Extensive unstocked areas for which money for planting or seeding is not likely to be available in the near future.
- Extensive areas of stagnated timber below utilizable size and areas that will become stagnated or deteriorated to the point of not producing utilizable wood unless and until necessary cultural work is done but for which the financing is not likely to be available in the immediate future.

General observations

Two general observations can be made as the result of this analysis of forest land stratification on the National Forests.

(1) Before timber inventory data can be organized to provide clearcut and accurate guidelines for management, the plans for land use must be carefully developed. Definitive multiple use plans require a broad base of knowledge about land stability, watershed characteristics, ecology, and resources. In other words, timber inventories and plans are not and cannot be independent entities but are subordinate aspects of a total multiple use planning process. Anything less than complete and definitive multiple use plans results in timber being cut where it shouldn't be cut and roads being built where they shouldn't be built on the one hand, and misguided reservations of timber on the other.

(2) Some top quality timber lands may not be used for timber production because they have other more important values. However, on lands classified as not suitable for timber growing (or otherwise withdrawn from such use) the production of timber is generally lower than on lands that remain part of the timber growing base. Thus, although tightening of timber production standards reduces the actual area of productive forest land, it will not proportionally reduce the timber production capabilities. In fact, any increase in management expenditures will likely buy greater increases in future timber output if concentrated on the smaller area of better quality land.

Results

The areas of the timber growing bases of the six National Forests as estimated in the previous inventory and as revised in this study are compared in table 1. This reveals very clearly how misleading such information can be if land suitability for timber use, land capability, and land availability are not adequately considered. It is well to remember, though, that land use intentions change and they have changed in recent years. For that reason, the earlier data reflects in some cases outdated thinking relative to use expectations.

The specific reasons for the decline in the timber base on each National Forest are shown in table 2. As mentioned earlier, factors that cause reduction of the timber growing base differ from place to place. However, one consistent result of careful reexamination was the elimination of areas from timber production plans because other uses and values are more important than timber yields and timber production. In many cases this conflict is based less on the actual cutting than it is on the roads made necessary by the cutting.

LOW PRODUCTIVITY

If forest land is to be considered part of the timber growing base, it must be capable of growing at least 20 cubic feet per acre per year; this is a longstanding Forest Service standard. One may properly ask whether this is the best standard for all places. It probably isn't, but we have not tried to solve that problem in this study. Rather our attention has been directed to the question of how well this existing standard has been applied (fig. 3).

Table 1. — Comparison of timber growing base areas by study unit, previous inventory, and 1969 inventory

Study unit	Previous inventory		1969 study inventory	Difference	
	Year	*Thousand acres*			*Percent*
Lolo area,[1] R-1	1966	745.2	629.1	116.1	-16
Arapaho N.F., R-2	1958	668.4	399.6	268.8	-40
Coconino N.F., R-3	1961	[2] 793.5	568.6	224.9	-28
Boise Area,[1] R-4	1964	385.3	273.3	112.0	-29
E. Klamath W.C., R-5	1968	420.1	372.3	47.8	-11
Gifford Pinchot N.F., R-6	1960	[3] 1,041.2	921.6	119.6	-11
Total		4,053.7	3,164.5	889.2	-22

[1] *Portion of National Forest.*
[2] *731.8 thousand acres classed as operable; 61.7 thousand acres classed as nonoperable.*
[3] *Area adjusted to correct for adjustment made in total area estimate for the Working Circle.*

Table 2. — Differences in estimates of timber growing base area, in thousand acres, between study inventory and previous forest inventory by unit and cause

Study unit	Total difference	Differences due to:					
		Low productivity	Unstable and unusable land[1]	Isolated patches and stringers	Land use conflicts[2]	Deferred	Land exchange sampling error
	Thousand acres						
Lolo Area,[3] R-1	116.1	--	23.4	--	32.7	58.9	+1.1
Arapaho N.F., R-2	268.8	67.2	2.2	9.9	127.5	64.9	-2.9
Coconino N.F., R-3	224.9	57.3	[4]108.3	[5].3	36.8	22.2	--
Boise Area,[3] R-4	112.0	23.5	25.6	11.2	43.3	5.6	+2.8
E. Klamath W.C., R-5	47.8	7.9	--	37.9	2.3	--	-.3
Gifford Pinchot N.F., R-6	119.6	17.2	10.1	--	68.3	19.3	+4.7
Total	889.2	173.1	169.6	59.3	310.9	170.9	5.4

[1] *Includes rock talus, rock land, and other unusable Forest soils.*
[2] *Crest and special multiple use zones are included in this category.*
[3] *Portion of National Forest.*
[4] *Over 100,000 acres are stable but unusable for timber production because of other soil factors.*
[5] *Most isolated patches and stringers on this unit were on unusable Forest soils.*

We found that the standard has not been applied uniformly or accurately. The usual procedure has been to determine soil productivity (site quality) from age-height relationships of dominant trees. Growth capability has then been determined from yield tables or yield equations based on the yield tables. Inherent in the procedure is the assumption that the area being evaluated can support as many trees as the land on which the yield table data were collected. This is not always true and generally is not true in stands located on the more arid fringe of the forest. In areas of low rainfall each tree requires more room than is "normal" to fulfill its moisture requirements. Thus, "full stocking" in such instances may be considerably below yield table levels. In any locality, rock outcrops, shallow soil, or soil variations may preclude stocking at yield table levels (fig. 4).

All inventory samples were examined carefully in areas where it appeared that stocking constraints might exist. This required consideration of certain ecological subtleties. For example, in some localities, the presence of a juniper tree (a noncommercial species) would not necessarily indicate that a commercial species such as ponderosa pine could grow there. Yield table estimates of growth were discounted in proportion to the stocking capability.[3] For example, if the information available indicated that only 50 percent stockability was obtainable, then the yield estimate derived from the site tree measurements and yield equations was reduced 50 percent. Field samples were classified as unproductive forest land and excluded from the timber growing base if they failed to meet the 20-cubic-foot standard which included consideration of both site and stocking capability.

Table 2 shows that many stands formerly considered to be part of the timber growing base don't measure up to the standard when

[3] *For the lack of a better basis, it was generally assumed that the existing tree stocking on marginal areas (or the stocking formerly present if the area had been disturbed) is the maximum the land could support.*

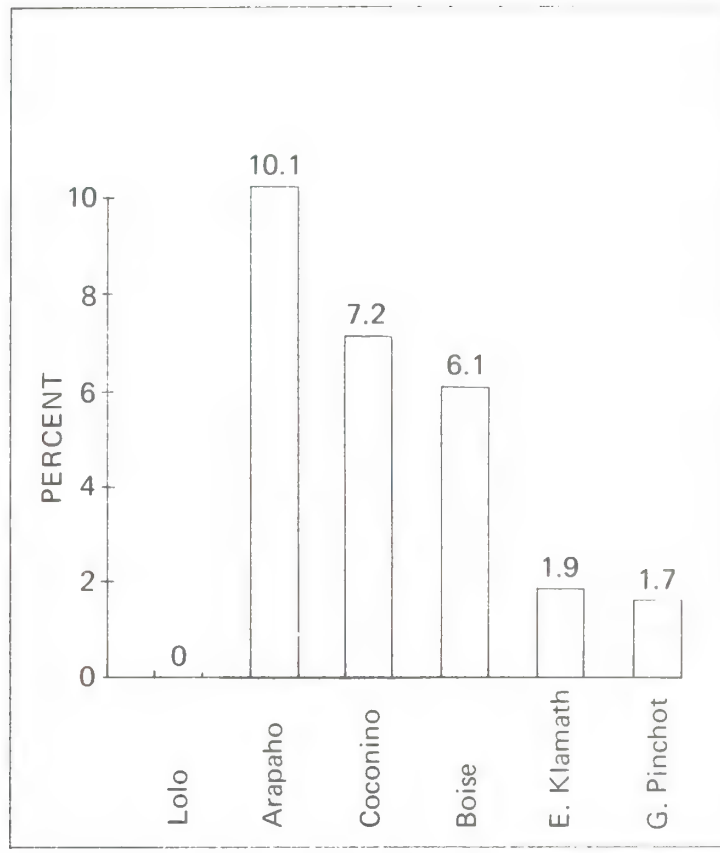

Figure 3. — Reductions in the timber base because of low productivity.

stockability is taken into account. As would be expected, the submarginal forest is most common in the central and southern Rockies.

LAND INSTABILITY

Each cooperating Region either made or had already completed a detailed or extensive soil survey for the National Forest included in this study (fig. 5). As part of the study, Forest Service soils-and-hydrology specialists then classified the forest land according to suitability for timber use, taking account of the basic structural stability of the slope, susceptibility of the soil surface to erosion, and the capacity of the land to receive, store, and discharge water. From such information they delineated the following classes of forest land on maps:

(1) Stable forest land usable for timber production with present timber growing and harvesting technology.

(2) Unstable forest land potentially usable for timber if there are improvements in timber growing and harvesting technology requiring fewer roads and less on-the-ground skidding of logs.

(3) Unstable forest land completely unusable for timber production because it is extremely susceptible to mass land slumps, flows, and slides or because the soil surface would wash away too readily if the vegetation were seriously disturbed. Snow avalanche or potential avalanche areas, rock talus, and other forms of rock land are also included in this category though the land itself is not unstable. On the portion of the Lolo National Forest studied, for example, much of the land in the "unstable" category is rock land and rock talus. On the Arapaho, mass land move-

Figure 4. — Ponderosa pine growing on a very poor site, Ashley National Forest in Utah. Timber could be harvested from areas such as this one, but the establishment of a new stand would be difficult and costly. Small wood values and big problems should rule such land out of the timber growing base.

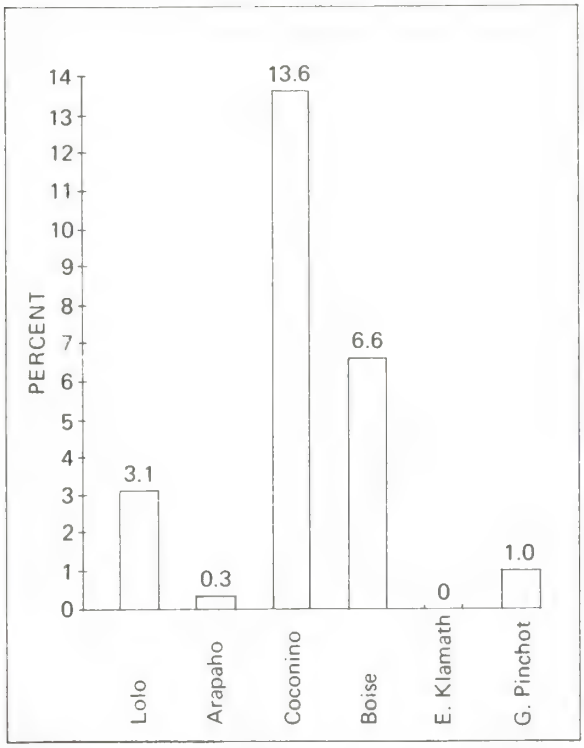

Figure 5. — Reductions in the timber base because of land instability. (Amounts shown for Lolo and Coconino include other soil factors, see table 2.)

ment is the principal problem, but it is not extensive. On the Boise, the unstable category is made up primarily of granitic soils highly susceptible to both surface erosion and mass slumps.

Land instability is a localized problem. On some National Forests it is not an important factor. In others, like the Boise, it is the most crucial single consideration in land classification.

SMALL ISOLATED PATCHES

Throughout the Western United States, forest land capable of producing timber crops commercially is located within a broad or narrow elevational range that varies by latitude and rainfall patterns. At lower extremes it generally fades into noncommercial timber, brush, and grass. At the upper elevations, subalpine timber and shrubs take over. In both the lower and upper transition zones those trees that are of commercial quality often occur in small scattered patches where, for one reason or another, there is greater moisture or deeper soil (fig. 6).

In most of the previous timber inventories, forest land area was estimated from point samples on aerial photographs. Even very isolated patches of timber land as small as 1 acre in size were considered to be timber growing land if they met the other requirements. Experience has shown this to be a faulty procedure because on many such areas the costs of, and damages from, utilization are more than the trees are worth.

In our analysis, no area smaller than 10 acres was considered usable for timber growing. Areas of productive forest land from 10 to 40 acres were considered usable only where they were close to larger bodies of forest land and could be utilized along with the main forest or were otherwise highly accessible. In all cases, the criteria of size and accessibility for these 10 to 40 acre areas were developed locally by National Forest and Regional personnel (fig. 7).

Table 2 indicates that the small isolated patches of timber excluded on two Forests (Lolo and Gifford Pinchot) did not account for much acreage. On the East Klamath Working Circle and on the Boise National Forest, however, large acreages were excluded due to size

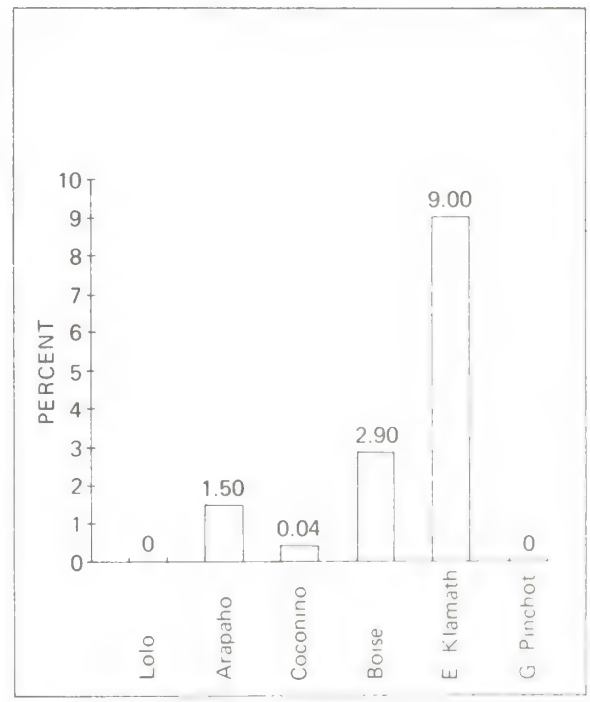

Figure 6. — Reductions in the timber base because of isolated stringers or small patches.

Figure 7. — Small scattered patches of Douglas-fir on the Challis National Forest in Idaho. It is highly questionable whether the timber is worth the effort of getting it out. Also, roads and skid trails that would be created by logging would produce lasting scars that can hardly be justified by timber values. Many such stands provide extremely important wildlife cover.

WIKSTROM J. H. and S. BLAIR HUTCHISON

1971. Stratification of forest land for timber management planning on the western National Forests, USDA Forest Serv. Res. Pap. INT-108, 38 p., illus.

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and isolation. The impact of these exclusions on timber yields is likely to be relatively light in most cases because the yield capability of the small forest patches tends to be low. Also, shallow soils and/or limited precipitation tend to make regeneration of new stands slow and difficult. In fact, severe disturbance of many such stands will cause them to revert to some nonforest cover type.

LAND USE CONFLICTS

When considering the effects of land use plans on timber availability, two points should be kept in mind:

First, land use situations vary greatly from National Forest to National Forest and also within the individual Forests. The situation in one travel influence zone, for example, may permit extensive timber cutting and in another little or no cutting.

Second, land use requirements are always changing and never will be static. There have been many changes in the demands upon these Forests since the previous timber inventory (fig. 8). Consequently, the differences shown in table 2 reflect both changes in forest land use and the results of a more critical look at forest land use.

The area *excluded* from the timber growing base for land use reasons includes only those areas on which no logging is planned beyond the salvaging of dead, dying, and hazardous trees. On other areas in the timber growing base,[4] timber utilization will be less than complete due to priority of other values such as recreation, esthetics, etc.

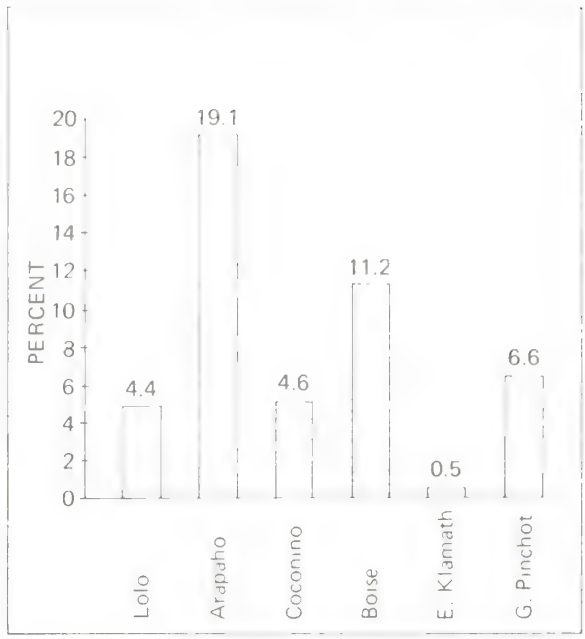

Figure 8. — Reductions in the timber base because of land use conflicts.

[4] *In the past there has been some confusion about how to define commerical forest land (the timber growing base). Actually, it is not related* per se *to cutting. In other words, timber has been and will be logged from noncommercial areas. Commercial forest is land that is being or will be used in the growing of timber crops for industrial use where management inputs are made for this purpose.*

Effect of criteria used on productive capacity

The timber harvest that can be sustained from any forest area depends upon three factors:

- The amount of forest area that is suitable and available for timber production
- The productive capacity of this land
- The intensity of timber management

In the short run, of course, the cutting level also depends upon the amount of merchantable volume immediately available.

Comparison of timber volume estimates of an earlier and a current inventory is for the most part risky because of the impact of cutting in the interim period. Also, during the interim between the two inventories for any unit, improvements have been introduced in volume estimating techniques. Two separate compilations were made for the Coconino Forest using the 1969 data; this enabled us to avoid the above problems and more realistically compare impact of the factors studied on the timber base area with impact on volume and growth capacity. The first estimate of timber base area, volume, and growth was based on the subjective field classification of inventory volume samples; this is the way inventory classification has been handled in the past. The second compilation was made by using study criteria.

It is significant that the reductions in the timber volume were about the same as the reduction in growing base area, but the impact on growth capacity was much less. The following tabulation shows these reductions:

	Percent
Timber growing base area	28
Timber volume	29
Growth capacity	18

The fact that there was a greater reduction in volume than in growth capacity suggests there has been proportionately more logging on the more productive land. Further analysis of growth capacity leads to the conclusion that following logging the better sites have regenerated more rapidly.

The real effect is less. — The 22 percent reduction in the estimate of timber growing base for the six National Forests does not represent an actual 22 percent loss of area and productivity for timber growing. It is true that the awakening interest in forest values other than

timber has placed additional constraints on timber growing opportunities. However, the large reductions reported here are mainly reductions in estimates rather than reductions in fact. For example, thousands of acres of very steep and unstable lands and areas not capable of producing 20 cubic feet of wood annually should never have been called suitable and available for timber growing in the first place. The reduced estimates of timber growing base suggested by the findings of this study, therefore, are not so much because of recent encroachments of other uses on the timber growing base as they are a matter of more realistic estimation of this base.

In recent years there has been growing recognition that important factors affecting suitability and availability of forest land for timber use have been overlooked in timber inventory planning. In many cases, managers of National Forests have made judgment adjustments of timber inventory estimates to correct for factors not considered in timber inventories. As indicated in table 3, although the estimate of the timber growing base for the six National Forests studied was 4.1 million acres, the cutting levels established following completion of the inventories for these Forests were based on 3.5 million acres being used for timber production. In some cases, subsequent reevaluations have resulted in further changes in the timber growing base for purposes of calculating the allowable cut.

Table 3. — Area of the timber growing base: from previous inventory; area used in management planning from previous inventory; and, area from study inventory by unit

Study unit	Area of timber growing base		
	Previous inventory	Management plan	Study inventory
	Thousand acres		
Lolo, R-1	745.2	745.3	629.1
Arapaho, R-2	668.4	446.0	399.6
Coconino, R-3	793.5	599.9	568.6
Boise, R-4	385.3	368.7	273.3
E. Klamath, R-5	420.1	420.1	372.3
Gifford Pinchot, R-6	1,041.2	960.5	921.6
Total	4,053.7	3,540.5	3,164.5

Recommendations

If any overall criticism of past practice is in order it is that the effort going into the development of coordinated plans for the management of National Forests has been inadequate. The major problem is lack of basic planning information, much of which is costly to obtain.

It could be said in short that the problem is inadequate financing for basic data collection, analysis, and planning. The problem is more than one of financing for timber inventories. The timber resource cannot be described meaningfully unless it can be described within the context of the land, ecology, and land use situation. Thus, there must be balanced financing for soils-hydrologic surveys, ecological habitat surveys, and resource inventories.

The data presented indicate that when there is an absence of adequate information about the land and ecology and there is also inadequate multiple use land management planning, then the tendency is to overestimate the timber growing base area. This in turn results in a temporary inflation of timber cutting levels. *Far more serious, however, is the fact that to include forest land in the timber growing base that will not, or probably will not, be used for the production of industrial wood is to imply the timber growing base is larger than it really is and the need for management effort is to that degree being falsely discounted.*

The six Forest Service Regions have been quick to recognize the implications of the study findings and many of them have already moved rapidly to correct deficiencies in past procedures. In general the effort has been to relate the timber inventory classification to improved multiple use plans. This has required accelerating soils-hydrologic surveys to provide land stability information in advance of timber inventories. In addition, where forest land management activities are influenced by physiography, ecology, accessibility, or use objectives, maps are being prepared to permit classifying the timber inventory data accordingly.

There is a premium on "in-place" information for National Forest planning. Unless mapping is used, it is impossible to relate sample plot information about the timber-to-land capability, land use plans, and other pertinent characteristics that are area related.

The Forest Survey Research Units in the West are now cooperating with National Forest System Timber Inventory staffs in designing timber inventories that relate the timber "in-place" to the land, habitat, and land use situations and provide more "in-place" information on the timber itself. The timber inventories now being designed and planned vary in detail from Region to Region, depending on the individual Region's timber data situation and data handling capabilities. Although changes and improvements are already underway, it is still appropriate to observe that thoroughly meaningful timber inventories require progress along the following lines:

- *Multiple Use Planning Must Be Improved*

  The principal conclusion of the Intermountain Station and the cooperating Regions and Forests is that the taproot of the problem of forest land stratification is in multiple use planning. Functional plans can be no better than the multiple use plans to which they are related. Multiple use plans must reveal the land use situation accurately and completely.

  To be complete, the multiple use plan must give specific details about the nature of the management planned on the land available for timber growing on a modified basis only so that the impact of the modifications on expected yields can be determined (fig. 9).

Figure 9. — Example of good cleanup after logging, keeping roads up out of stream bottoms, and use of a residual strip to protect streambanks and aquatic environment.

- *A Coordinated Approach Is Required To Build an Adequate Data Base for Forest Land Management Planning*

  Timber inventories should not be undertaken without making full use of the information required to relate the timber to the land and land use situation. In other words, there must be closer coordination of timber inventory with soil-hydrologic surveys and studies, ecologic surveys, and multiple use planning.
- *Increased Funding for Surveys and Resource Inventories Is Essential*

  Substantial increases in funding will be required in the future for the collection and development of planning information. The more intensive the management, the more intensive must be the effort to develop planning information. Demand for forest land for all uses has increased in recent years, requiring that the National Forests be managed more intensively. However, work in the area of basic data collection and information development for planning have not kept pace with the need.
- *Research Effort in Forest Management Planning and Inventory Techniques Should Be Increased*

  More data collection will not by itself produce a solution to forest land management problems. Although a significant part of the problem is lack of data, a major difficulty is the need to make more effective use of the data collected for management planning. There is a need, also, to improve data collection techniques both to achieve increased efficiency and to decrease data collection costs.
- *Timber Inventory Planning Must Be Improved*

  The failure of timber resource statistics to serve the information needs of National Forest planning as well as they should is partly the fault of overpreoccupation with certain standard data required for national statistics. The preoccupation with responsibility for standard statistics for Washington Office use has diverted attention from the dynamic and more detailed informational needs of individual National Forests for planning purposes.

  A prerequisite for an adequate inventory of the timber resources of any National Forest, therefore, is a carefully prepared plan that identifies the objectives of the planning effort, lays out the analyses required, specifies the data needed to accomplish these analyses, and describes how the data are to be collected.
- *A MORE DETAILED STRATIFICATION OF FOREST LAND IS NEEDED FOR PLANNING*

  Experience of managers and management planners indicates that a simple "commercial-noncommercial" division of forest land is too general and not adequate to meet National Forest planning needs even at the national level. Neither is it adequate to divide forest land only on the basis of quality or yield-capability classes. Other land characteristics such as steepness of slope, land stability, access, kind of soil, and ecologic or habitat type can have a very significant effect on the cost and opportunity for using the land for timber growing. In addition, the amount and condition of the timber occupying a given area can be a major factor limiting the opportunity for usage. In other words, it is essential to describe the forest land in terms of all the factors that affect its use for timber production and to describe the timber in relation to the land. Furthermore, it is necessary to develop a classification of the timber growing base area that reflects degree of management need and opportunity. It will, however, be impossible to do this without first getting agreement throughout the Forest Service on the planning and analysis models to be used.

APPENDIX

Procedure for timber inventory

Timber inventories generally are based on a double sampling scheme. Initial sampling on aerial photos involves classifying a large number of photo points into broad forest land classes (nonforest, nonproductive forest, and productive forest). For field sampling, the productive forest category is further categorized into a number of strata based on type stand or volume of timber. The field samples provide: (1) information to verify the photo point classification; (2) tree measurement data from which estimates of timber volume can be made; and (3) general information on the condition of the forest.

This double sampling procedure was used on all but the Gifford Pinchot study unit where a single sampling procedure was employed using only field samples. Of the timber inventories used, none were designed to consider all the land and land use attributes evaluated in this study. Information on these attributes was developed afterward and the inventory data recompiled to reflect the influence of land and land use characteristics.

For this study, map data were used and photo points for each study unit were further classified to reflect land use and land characteristics. Basic information was obtained from: timber stand and/or type maps, multiple use land management plan maps, and maps showing soil type and land stability situations. Multiple land use management maps for the study areas were updated to indicate all forest land where management to meet nontimber land use commitments would preclude or restrict timber production. In addition, management intent was specifically described in detail so that impact on timber use and yield could be assessed.

Another map was prepared for the study unit showing undeveloped land for which no access was planned during the next 10 years. Also shown were areas of peculiar ecology or soil situations that could not be used for timber production because of unsolved timber growing problems. In addition, the timber inventory on the study unit was supplemented by the collection of data on stocking capability and description of small isolated patches and stringers of trees.

DOUBLE SAMPLING PROCEDURE

The stratification procedure and results with the double sampling system are illustrated here by using data from the East Klamath Working Circle, Klamath National Forest, located in the Upper Klamath River area of northern California and southern Oregon. This Working Circle, 551,099 acres in size, is dominated by steep slopes, though the soil is relatively stable. The reconnaissance soil survey indicated that most of the forest land is usable now for timber production or potentially usable with some improvements in technology. Some of the area, particularly at higher elevations, is rugged country having productive forest land that occurs in pockets and patches intermixed with nontimber base forest land and barren, rocky areas. At lower elevations the forest cover is broken, with forest areas intermingled with nonforest land. The timber resource on the Working Circle was inventoried for timber in 1968. Utilizing recent aerial

Table 4. — Number of photo points and field samples by land class and photo volume stratum within productive forest land East Working Circle, Klamath National Forest

Land class	Photo sample stratum	Number photo points	Number field samples
Productive forest	1	215	17
	2	818	58
	3	518	32
	4	546	25
	5	606	30
	6	309	13
	7	226	11
	8	39	2
	--	--	--
Subtotal	--	3,277	191
Nonproductive forest	--	692	41
Nonforest	--	342	16
Total	--	4,311	248

photo coverage, 4,311 photo points were classified, giving an area weight per sample point of 127.8355 acres.

$$\frac{551,099}{4,311} = 127.8355$$

The estimate of area by class of land based on the photo samples was as follows:

Land class	Number photo points	Acres
Productive forest land	3,277	418,917
Nonproductive forest land	692	88,462
Nonforest land	342	43,720
Total	4,311	551,099

Every nth photo point sample was drawn as a field sample and visited on the ground. Tree measurements were taken only when the field inspection indicated the sample (1 acre around the photo point) was productive forest land. Also, to improve sampling efficiency, productive forest land photo samples were classified into eight sampling strata prior to field sampling.

Table 4 shows the total number of photo and field samples by class of land and by sample stratum for the Working Circle. As mentioned previously, the field sample information was used to verify the classification of land made from photo point interpretation. The results of the field verification were then used to adjust the photo sample area estimates to correct photo sample misclassification.

Two estimates of area by classes of land were made: (1) The first one was based on the results of the field classification of sample points selected for field sampling as initially carried out by the timber inventory staff (table 5); the second one was based on a classification of field samples using study criteria. The estimates of area by broad land class from the photo point sample were adjusted by using the timber inventory field classification as a base. The results were as follows:

Land class	Acres
Productive forest land	416,617
Nonproductive forest land	101,692
Nonforest land	32,790
Total	551,099

Table 5. — Timber inventory, photo and field classification of field samples by land class, East Working Circle, Klamath National Forest

Land class photo sample	Photo sample stratum	Field classification of land			Total
		Productive forest	Unproductive forest	Nonforest	
		Number of locations			
Productive forest	1	17	--	--	17
	2	53	5	--	58
	3	32	--	--	32
	4	23	2	--	25
	5	28	2	--	30
	6	13	--	--	13
	7	13	1	--	14
	8	2	--	--	2
Subtotal	--	181	10	--	191
Unproductive forest	--	6	35	--	41
Nonforest	--	3	1	12	16
Total	--	190	46	12	248

Using study criteria to classify field samples produced some interesting results. First, 15 of the locations were taken at points on land identified on maps as noncommercial or nonforest. These points were on patches of forest land that were at least an acre in size but not considered suitable for timber growing. Second, when stocking capability was considered, some of the field locations initially classified as productive forest land proved to be in the nonproductive category.

An additional seven field locations taken on forest land initially classified as productive forest land proved to be in the nonproductive category when the current study criteria were used. Also, five of the nine field locations taken on nonproductive forest land and nonforest land and classified by the original timber inventory as productive forest land were also, following field examination, judged nonproductive by the current study criteria.

The productive land lost by reclassification of field samples was not, however, as great as the preceding discussion might suggest. This was because much of this reclassified land had already been excluded for other reasons.

The classification of the field samples by use of study criteria is shown in table 6. Area estimates by classes of land and multiple use land management zones following study procedures are shown in table 7.

Table 7 shows these new estimates of productive forest land area by multiple use management zone, excluding the patches described above, as well as the area excluded because of limited productivity. Of significance also in table 7 is the area in travel and water influence zones. Forest managers currently believe that management requirements will impose some limitation on timber yields in these zones.

Another significant factor in the management of the timber resource of the East Klamath is that some of the area is only potentially usable because of land instability, problems of access, or silvicultural problems. Table 8 shows the area suitable for timber use outside the crest zone available now and potentially available with full yields and modified yields expected.

SINGLE SAMPLING PROCEDURE

In the Pacific Northwest Region (Region 6) a single field sample was used to estimate area

Table 6. — Photo and field classification of field locations used in final area estimates (samples falling on isolated patches excluded), East Working Circle, Klamath National Forest

Photo land class	Sample stratum	Field classification			Total
		Productive forest	Nonproductive forest	Nonforest	
		Number of Locations			
Productive forest	1	16	--	--	16
	2	53	2	--	55
	3	31	--	--	31
	4	23	--	--	23
	5	27	1	--	28
	6	13	--	--	13
	7	13	1	--	14
	8	2	--	--	2
Subtotal	--	178	4	--	182
Unproductive forest	--	1	36	--	37
Nonforest	--	--	2	12	14
Total	--	179	42	12	233

Table 7. — Final estimate of area in acres by class of land and multiple use land management zone, East Working Circle, Klamath National Forest

Multiple use zone	Area by class of land				Total
	Productive suitable	Productive unsuitable[1]	Unproductive	Nonforest	
	Acres				
Crest	2,257	1,765	2,114	1,151	7,287
General forest	357,747	35,712	93,722	29,530	516,711
Travel influence	4,754	1,776	2,515	671	9,716
Water influence	9,778	2,828	3,341	1,438	17,385
Total	374,536	42,081	101,692	32,790	551,099

[1] *Acres of productive forest land in small isolated patches (as small as 1 acre) in delineated areas of rocky noncommercial or nonforest land.*

Table 8. — Area in acres of productive forest land suitable for timber use at full yields and with modified yields by availability class, East Working Circle, Klamath National Forest

Availability class	Full yields expected	Modified yields expected	Total
	Acres		
Available now	335,190	13,826	349,016
Potentially available:			
Stable land with timber growing and access problems	12,719	--	12,719
Unstable, potentially usable land, no other problems	8,715	706	9,421
Unstable land and timber growing and access problems	1,123	--	1,123
Total	357,747	14,532	372,279

and volume. Field samples were mechanically spaced 1.7 miles apart. In the inventory of the Gifford Pinchot Working Circle in 1960, three subplots were taken at each sample location. In the 1969 inventory, the locations established in 1960 were revisited and a standard 10-point plot was established.

In the 1960 inventory, the total area of the working circle was sampled. By contrast, in the 1969 inventory, the obviously noncommercial forest and nonforest land were mapped. Also, a recent soil map and an updated multiple use map were used to further classify locations so that the area of "apparent commercial forest land" could be further stratified.

Before the 1960 and 1969 inventories could be compared, it was necessary to adjust the 1960 estimates. After 1960, a new estimate of area in the Forest was made, recomputing area township by township and section by section where necessary. A new area weight was computed for each location and subplot to correspond with the corrected total area of the Working Circle. Following are the earlier and the current corrected area estimates for the Working Circle by broad land class:

Land class	Earlier estimate	Current corrected estimate
Commercial	1,029,477	1,041,252
Noncommercial	74,553	75,408
Nonforest	38,519	38,960
Total	1,142,549	1,155,620

1969 Inventory

In 1969, the total area in the Working Circle was 1,161,420 acres. The difference between this and the corrected 1960 estimate shown above was due to land exchange and sampling error.

Of the 1,161,420 acres, 135,030 acres were mapped as obviously noncommercial or nonforest. The remaining 1,026,390 acres in the Gifford Pinchot Working Circle plus the Snoqualmie Working Circle of 79,499 acres were field sampled in this inventory utilizing 580 field locations. The area weight of each field sample was 1,906.7052 acres.

$$\frac{1,105,889}{580} = 1,906.7052$$

As a result of field classification and measurement, nine of the locations on the Gifford Pinchot Working Circle were classed as noncommercial. The area associated with these was taken out of the "apparent commercial forest land class" and combined with the "obvious noncommercial" to arrive at total noncommercial. This resulted in area estimates by broad land class as follows:

Land class	Acres
Apparently commercial	1,009,230
Noncommercial	106,280
Nonforest	45,910
Total	1,161,420

Because the sample was so small, it was not possible to further stratify the "apparent commercial forest" by land type and use on a sample basis. This was done by using soil-hydrology maps and multiple use maps with stand or type maps. The samples were used only to identify the categories of land in which to make the correction for field location classification. To illustrate, four of the field locations reclassified from commercial to noncommercial in the field were on forest land mapped as marginal for timber use. The correction for area associated with these four locations was therefore carried into this category.

Area estimates were made utilizing maps. One set of maps showed forest land considered marginal for timber use because of problems of access and timber growing problems. Another set of maps showed land in management units as follows: (1) under study to determine proper land use (deferred); (2) unavailable for timber use; and (3) available for timber use under modified management with partial yields expected.

The results of the 1969 inventory summarized, and using study criteria, are as follows:

Land class	Area in acres	
Category A (commercial):		
Full yields expected	649,064	
Modified yields expected	141,611	
Total — Category A		790,675
Category B (marginal):		130,952
Total — *Timber Growing Base*		921,627
Category C (noncommercial):		
Unproductive forest land	106,280	
Unavailable productive forest land:		
Experimental forest	9,899	
Developed camps & administrative sites	4,853	
Devoted to other uses	53,540	
Total — Category C		174,572
Category D (deferred):		19,311
NONFOREST LAND		45,910
TOTAL ALL LAND		1,161,420

Details on other units

REGION 1 — LOLO UNIT

The Ninemile and Superior Ranger Districts of the Lolo National Forest were used as a study area because of the availability of soils data from a recent soil inventory. This area of 835,133 acres lying west of Missoula and extending to the Idaho boundary is quite steep and rugged; however, the land is sufficiently stable to withstand the strain of timber use. Use of the area by people has increased greatly in recent years. As a result of public pressure to create more recreation capacity, an especially scenic area of 58,953 acres is now under study to determine the most appropriate use. This is the area shown in the "deferred" category in table 2.

Another factor affecting use is the large herds of deer and elk in the area. The large fires that occurred in the area 50 to 60 years ago destroyed forest and created large brush field desirable for big game. Many of these burned-over areas restocked with timber; however, sizable areas still support brush and browse and only sparse timber cover.

Because the area has proved to be desirable big game habitat and has attracted so much attention as a hunting area, big game management must be given appropriate attention. This must be done through timber harvesting and management of forested areas to improve habitat. For areas critical to the maintenance of game herds, it often means maintaining brush and browse cover.

Inventory Problems

In the process of relating timber to both the forest land and forest land use, important data problems were noted. While the study area generally is made up of highly productive timber land (see table 9), as is typical of mountainous country, there are areas of rock talus, exposed bedrock, or bedrock with insufficient soil cover to be considered usable for timber growing. Such areas often support enough timber cover to be called forest land and in the absence of soils data may be included in the estimate of timber growing area. On the study portion of the Lolo National Forest it was discovered that 14,002 acres of unusable rock land had previously been included in the timber growing base.

On the Lolo area it is also significant that because of repeated harsh burns and soil loss following these fires, some areas can no longer be considered timber growing land. In the past, timber inventory has taken the presence of tree stumps and snags as evidence of forest land. In the absence of ecological data they could not do otherwise. In connection with this study, the Forest staff, using ecological criteria, identified 9,433 acres that had been misclassified as productive forest land.

Two other problems became apparent in analyzing the situation; however, data were lacking to quantify them. One problem involved areas that supported stands of stagnated saplings and small pole-size trees that were not likely to ever develop into utilizable timber. It would be desirable if such stands could be identified and treated as a special category in forest land management planning.

The second problem also involves ecology. Apparently, there are areas of peculiar ecology that present difficult timber regeneration problems. It is possible that these could be identified by using present ecological knowledge, but funds have been too limited to permit it.

Table 9. — Timber growing base area in the Lolo study unit by broad soil quality classes as estimated from soil type map

Soil quality class	Timber site range[1]	Acres
Very good	65+	448,729
Good	50-65	70,770
Fair	40-50	81,184
Poor	<40	28,452
Total		629,135

[1] *Tree height at age 50, in feet.*

Summary of the Lolo Unit

Following is a summary of the area of the Lolo study unit by broad land management categories:

Land class	Area in acres	
Category A (commercial):		
Full yields expected	484,448	
Modified yields expected	116,235	
Total — Category A		600,683
Category B (marginal):		28,452
Total - *Timber Growing Base*		629,135
Category C (noncommercial):		
Unproductive forest land	36,535	
Unsuitable forest land:		
Rock land & other unusable land	23,435	
Unavailable productive forest land:		
Crest zone	25,070	
Use conflicts	7,598	
Total — Category C		92,638
Category D (deferred):		58,953
NONFOREST LAND		54,407
TOTAL ALL LAND		835,133

REGION 2 — ARAPAHO NATIONAL FOREST

The Arapaho National Forest is an extremely rugged mountain area with numerous peaks above 11,000 feet. The forest cover is broken by extensive rocky areas especially at the higher elevation and by areas of sagebrush and other nonforest vegetation at the lower elevation.

Most of the timber on the Forest occurs between 7,000 and 11,000 feet where the growing season is short. Generally speaking, timber growing capacity of the land is low, averaging slightly over 40 cubic feet per acre of productive forest land per year. There are some good timber producing sites capable of producing in excess of 80 cubic feet of wood per acre per year, but these are limited.

The Forest is located at the back door of a city of a million people (Denver, Colorado). This combined with the unusual rugged mountain scenery and recreation opportunities has created a strong demand for nontimber uses on the Forest.

The timber inventory previous to this study was made in 1958 when forest use demands were less clear than they are today. Recreation and recreation-related developments since 1958 have taken a significant amount of area out of timber use. As shown in table 2, 127,563 acres of productive timber land can no longer be considered available for timber growing. This does not mean that no timber will be cut from this land. Trees removed in the process of perpetuating the environment will be utilized wherever possible. However, the land itself will not be managed for a timber crop.

In addition to the 127,563 acres not available for timber use, there are about 34,000 acres which will be used on a modified management basis but from which full yields cannot be expected if other forest land use objectives are met.

Land stability is not a major problem on the Arapaho National Forest. Patches of unstable land comprising only a little over 2,000 acres are too unstable to stand the strain of timber use (table 2). A substantially larger area is considered only potentially usable, pending improvement in timber harvesting technology:

Stability class	Acres of timber growing land
Unstable, potentially usable (Including 3,816 acres on slopes over 60 percent)	45,654
Stable land	326,455
Unclassified, assumed to be stable	27,462
Total	399,571

A major factor limiting timber use at present is steepness of slopes. Harvesting technology used in the area is limited to slopes under 40 percent. As the table relation below shows, a significant amount of the productive forest is on slopes steeper than 40 percent.

Slope class (Percent)	Acres of commercial forest land
0-40	343,144
41-60	52,611
Over 60	3,816
Total	399,571

Information Deficiencies

As on the Lolo, problems were also noted on the Arapaho that could not be adequately described by using the data available. The most significant of these problems was the lack of information to identify areas supporting stagnated stands not likely to develop to utilizable size and, therefore, of marginal value for timber use.

In addition, there is need for ecological data that will permit identification of timber growing problem areas.

Summary of the Arapaho National Forest

As previously indicated, forest land use, land stability, and steepness of slope are significant factors affecting timber production on the Forest. Following is an area summary for the Forest by broad land management classes:

Land class	Area in acres	
Category A (commercial):		
Full yields expected	308,026	
Modified yields expected	28,650	
Total — Category A		336,676
Category B (marginal):		
Potentially usable stable land:		
Full yields expected	11,790	
Modified yields expected	5,451	
Potentially usable unstable and steep land:		
Unstable 40-60% slopes	41,838	
Slopes over 60%	3,816	
Total — Category B		62,895
Total — *Timber Growing Base*		399,571
Category C (noncommercial):		
Unproductive forest land:		
Photo	45,418	
Field adjustment	67,185	
Productive unsuitable forest land:		
Unstable	2,193	
Isolated patches	9,908	
Productive unavailable forest land:		
Crest zone	21,889	
Travel-water influence	53,324	
Other use conflicts	52,350	
Total — Category C		252,267
Category D (deferred):		64,885
NONFOREST LAND		231,114
TOTAL ALL LAND		947,837

REGION 3 — COCONINO NATIONAL FOREST

The Coconino National Forest in northern Arizona was selected by the Southwestern Forest Service Region 3 as a study area. This forest of 1,774,710 acres on the Arizona Plateau is largely a ponderosa pine forest and is for the most part stable. Some fir and spruce occur, primarily in the San Francisco Peaks area of the Forest. A significant amount of the area is forested but the soil is not considered suitable for timber growing. Also, there are limited areas not considered operable at this time with the technology available.

Generally speaking, the Coconino National Forest is low in productivity. While there is some forest land (about 14 percent) capable of producing in excess of 50 cubic feet of wood per acre per year, the remainder has a yield

capability of from 20 to 50 cubic feet of wood per acre per year. A major problem in relation to productivity is at the lower elevational fringe of the forested zone. Much of this land simply will not support enough trees to meet the productivity level required for commercial forest.

Another major factor affecting timber inventory on this unit is the changing land use. Pressure on the Forest by people is increasing rapidly and as a result, an ever-increasing amount of forest land is being devoted to nontimber uses.

Summary of the Coconino National Forest

Normal timber inventory procedure. — The Coconino National Forest was studied at the same time it was being reinventoried for timber. As a consequence it is possible to directly contrast the study criteria and the land classification criteria applied in the reinventory.

The primary aerial photo point sample taken on the Forest involved 8,300 samples. Following is the estimate of area by broad land class based on those samples.

Land class	Acres
Productive forest land	902,522
Unproductive forest land	516,390
Nonforest land	355,798
Total	1,774,710

A subsample of 271 photo point samples was drawn for field checking of land class and measurement. The results of the field classification were then used to correct the primary sample estimates. As a result of the field check, 24 samples classed as productive forest land on the aerial photos changed to nonproductive. In other words, 24 of the field samples did not meet the productivity criteria of 20 cubic feet of wood per acre per year because of low site. Following are the corrected estimates of area by broad land class:

Land class	Acres
Productive forest land	854,355
Nonproductive forest land	564,431
Nonforest land	355,924
Total	1,774,710

Study criteria applied. — Using the additional data collected on stocking capability, it was possible to more realistically assess land productivity. In addition, it was possible to use available soil data for identification of land that, while supporting some timber, was from a soil point of view alone, not to be considered timber growing land. Also, it was possible to use available vegetation type information for identification of areas where the soil was adequate, but because of moisture limitations was not suitable to produce commercial tree species.

Productive forest land in the crest zone was considered unsuited for timber use. Also considered unavailable for timber growing was productive forest land in the special multiple use zone, including such things as experimental areas and designated natural areas and land in management units managed primarily for nontimber uses. Following are the results of applying the study criteria:

Land class	Area in acres	
Category A (commercial):		
Full yields expected	436,702	
Modified yields expected	41,267	
Total — Category A		477,969
Category B (marginal):		
Currently inoperable	67,804	
Fringe and low site areas	22,888	
Total — Category B		90,692
Total — *Timber Growing Base*		568,661

Land class		Area in acres
Category C (noncommercial):		
Unproductive forest land	682,557	
Productive unsuitable forest land:		
Noncommercial forest soils	108,285	
Isolated patches	287	
Productive unavailable forest land:		
Crest zone	210	
Special zone	15,974	
Use conflicts	20,605	
Total — Category C		827,918
Category D (deferred):		22,207
NONFOREST LAND		355,924
TOTAL ALL LAND		1,774,710

REGION 4 — BOISE UNIT

The Cascade and Garden Valley Ranger Districts of the Boise National Forest were used as the Intermountain Region's contribution to this effort. These two Districts are in the Idaho Batholith, a land formation well known for its unstable and highly erodible character. Much of the area is quite rugged and steep in addition to being highly erodible. The management of the land is further complicated by the fact that the area is a very important source of water. Also, the major streams support anadromous fish. The South Fork of the Salmon River, for example, is an important salmon spawning area.

Thus, these two Ranger Districts contain major areas which are extremely sensitive, but they also include some of the most productive timber land in the Intermountain Region of the Forest Service. Twenty percent of the commercial forest land in the study area has the capacity to produce in excess of 100 cubic feet of wood per acre per year. The landforming processes that shaped the area involved glaciation and left a lot of area of low productivity. Inventory procedures of the past have not adequately reflected this. As was indicated by data in table 2, over 23,000 acres previously classed as productive forest land lacked the required productive capacity when stocking capability was considered.

Demands for timber land for nontimber uses have also increased significantly in recent years. The rugged mountain scenery, the fishing streams and lakes, as well as the large and small game animals and birds attract large numbers of people. Around some of the lakes and along the more popular fishing streams, significant recreation complexes have already been developed and others are planned. In addition, the study area joins an established primitive area into which visitors to local dude ranches and camps make wilderness excursions.

Summary of the Boise Unit

Following is a summary of the area in the Boise Unit by broad land management categories:

Land class		Area in acres
Category A (commercial):		
Full yields expected	151,720	
Modified yields expected	47,045	
Total — Category A		198,765

Land class		Area in acres
Category B (marginal):		
Full yields expected	27,692	
Modified yields expected	46,831	
Total — Category B		74,523
Total — *Timber Growing Base*		273,288
Category C (noncommercial):		
Unproductive forest land	54,350	
Unsuitable forest land:		
Unstable land	25,579	
Isolated patches	11,233	
Unavailable forest land:		
Crest zone	27,127	
Use conflicts	16,180	
Total — Category C		134,469
Category D (deferred):		5,566
NONFOREST LAND		43,542
TOTAL ALL LAND		456,865

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Cover Photo: Spectacular view of north face of Gray Wolf Peak that rises abruptly above southwest shore of Gray Wolf Lake. St. Mary's Peak in center. A 12-year-old mountain climber in foreground.

USDA Forest Service
Research Paper INT-109
December 1971

WILDERNESS USE ESTIMATION: A PILOT TEST OF SAMPLING PROCEDURES ON THE MISSION MOUNTAINS PRIMITIVE AREA

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ABSTRACT

Methods for estimating wilderness recreational use were pilot tested during the summer and fall of 1968 in the Mission Mountains Primitive Area. The main basis for the estimating methods was trail register information. Intensive field sampling provided data on actual use to relate to registration data. Both ratio and regression methods produced estimates with acceptably small error terms (6 percent for estimated visits, in the case of the ratio estimates, for example), but the ratio methods seemed to have a small advantage over regression methods. Overall, 65 percent of the visitor groups were estimated to have registered, but there were substantial variations in registration rates associated with a number of factors--type of activity, mode of travel, length of stay, and weather. The registration rate patterns were generally similar to those reported from an earlier study in Oregon. Use of the Mission Mountains Primitive Area is described. Suggestions are made for wilderness use estimation and for increasing the effectiveness of trail register systems.

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INTRODUCTION

The rugged north face of Gray Wolf Peak as viewed from across the head of Gray Wolf Lake.

Wilderness is a fragile resource in both an ecological and an esthetic sense. Management of wilderness faces the difficult challenge of providing for the use of these areas while preserving the substantially unmodified ecosystem and the outstanding opportunities for solitude that are the essential characteristics of wilderness.

The impact of use on the wilderness resource cannot be understood or managed adequately without knowledge about the level and nature of that use. Many decisions need to be based on use data, for example, control of use by people and their horses, redistribution of use pressures, trail construction and maintenance, litter cleanup, campsite closures and rehabilitation, planning patrol routes for Wilderness Rangers, and minimizing conflicts between grazing and recreational use. Such decisions are hampered by the poor quality of wilderness recreation use estimates--among the poorest of recreation use data.

It is difficult to estimate wilderness use with even modest accuracy for obvious reasons. Wilderness visitors are highly mobile and are scattered widely over large areas, away from roads where observation and counting are easy. Users may enter a wilderness at many access points; several wildernesses have over 60 entrances.

Some wildernesses have no system of visitor registration; managers of most of the areas that do have a registration system are uncertain how registered use compares with actual use. This is a serious problem, particularly because of the rapid growth of use of National Forest and National Park Wilderness. National Forest visitor-days of wilderness use were estimated at only one-twentieth of developed campground use in 1946, but 20 years later this proportion had grown to about one-seventh. We should be skeptical about the figures, but the trend is undeniably strongly upwards. Use projections strongly suggest large future increases.[1]

This rising use is occurring on a land base of established wilderness that has remained almost unchanged in total area during the past 30 years; thus, these growing use pressures need to be managed. Use estimates in the past that have been based largely on informal observation, experience, and intuition are not acceptable today. Consequently, the need for sound estimates of wilderness use now is critical--before wilderness values are irrevocably damaged or destroyed.

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[1]University of California Wildland Research Center, Wilderness and recreation--a report on resources, values, and problems, ORRRC Study Report 3, Outdoor Recreation Resources Review Comm., Wash., D.C., 1962, pp. 235-236, and unpublished projections of the National Forest Recreation Survey (NFRS) indicate about an eight- to tenfold increase between 1959 and 2000.

PREVIOUS STUDIES

A backpacker looks out over the peaks of the southern portion of the Mission Range.

One of the first major efforts to develop ways of obtaining wilderness use information was made by Wenger and Gregersen in the Three Sisters and Mountain Lakes Wildernesses in Oregon during 1961 and 1962. Wenger (1964) tested the general effectiveness of unmanned, self-registration stations by placing two different types of registration boxes and forms and three different types of signs on trails and then interviewing visitors up the trails, out of sight of the registration stations. He concluded that self-registration was a promising approach to wilderness use estimations; that a single card per party, dropped into a box after completion, was superior to a book-type registration system; and that a firm but explanatory sign was best. Registration rates averaged 74 percent for both years and both areas. Location of registration stations had an important influence on response rates.

Wenger and Gregersen (1964) also reported on the association of registration rates and various visitor and location characteristics. They concluded that "raw" registration data contained biases, specifically underrepresenting riders, fishing and elk-hunting parties, one-person parties, and repeat visitors. Many other factors--including trails, day of week, size of residence community and distance to it, length of stay, and occupation--were unrelated to registration rates. They also concluded that the effects of nonresponse must be fully considered, and that modifications must be made in findings stemming from raw registration data. Wenger and Gregersen did not report on the conversion of registration data into use estimates.

Lucas (1964) studied recreational use of the Quetico-Superior area in Minnesota and Ontario, Canada. Traffic counters were placed on six major access roads and drivers were briefly interviewed as they left the area. The sample included about 4,000 groups--approximately 4 percent of the total traffic. Estimates of recreational characteristics for the total measured traffic for each road were made on the basis of the composition of the sample interviews. Error terms were not calculated. Visits were shorter than expected; 41 percent of the visitors did not stay overnight, and the average visit was only 1.75 days. Use was also very unevenly distributed--10 percent of the access points accounted for over half of the total visitor use for every type of user.

Thorsell (1968) studied wilderness visitor registration rates in Banff and Yoho National Parks in Canada. He observed six trail registration stations from a distance using binoculars without the knowledge of the visitors during a total of 95 hours. The stations were located at destinations in the interior of the Parks. Only 35 percent of the visitors registered, a much lower rate than in Wenger's Oregon study. Thorsell attributes this to the long form he used, which contained 19 questions. He also reported great variation in registration rates between locations, but this could be due to the small sample at each location. He classified all registration stations into three rates of response, and multiplied registration totals by the inverse of the assumed rate of response in order to estimate use. A similar procedure, based on an arbitrarily assumed 75 percent registration rate, was used by Thorsell (1967) in an earlier study of Waterton Lakes National Park. He reported that about 14 percent of Banff visitors used the trails, but in a very uneven distribution; the most popular trail out of a total of 56 trails in the Park accounted for 39 percent of the trail visitors. Steepness of trails did not seem to affect amount of use. Day use predominated (94 percent). Only 11 percent of the trail visitors penetrated over 5 miles into the backcountry.

Cushwa et al. (1965), and James and Henley (1968) conducted pilot sampling studies to estimate dispersed recreation use on large, general recreation areas. Their technique incorporated interviewing recreationists at established road checkpoints as they left recreation areas in nonwilderness situations.

STUDY OBJECTIVES

How can trail register data best be converted into estimates of wilderness use?

The most accurate information on wilderness use would probably be obtained from use of a registration or permit system administered directly by the area managers. The California Region of the Forest Service began requiring registration for wilderness visitors in 1971. This is costly; for most wildernesses, an unmanned self-registration system seems more feasible for now. But everyone does not register. As a result, registration data cannot be taken at face value; they must be converted to estimates of total use. How to make this conversion is the central objective of this study. This required (1) developing and testing a sampling design to provide estimates of current use, and (2) establishing relationships between use and trail register data so that use estimates with specifiable levels of precision could be made in future years, based on register data.

Several sorts of automatic counting devices were also tested. To aid in developing use estimation methods applicable to other wilderness-type areas having different kinds of use and varying conditions, we investigated the relationship of registration rates to visitor characteristics and to other factors such as season and weather. To help raise registration rates, we probed reasons for nonregistration.

The Mission Mountains Primitive Area was selected for study because it was large enough and complex enough to offer a thorough test of the sampling model but not so large as to make fieldwork for a pilot test too formidable. The Area's administrators felt it had a substantial amount of both foot and horse travel, day and overnight use, and summer and fall use; thus, the area seemed to be representative in important ways of many wilderness-type areas within the National Forest System.

Figure 1. – Map showing location of study area in the Northern Rockies.

The Study Area

The Mission Mountains Primitive Area is situated on the east slope of the Mission Mountain Range encompassing approximately 75,000 acres (fig. 1). The high country west of the crest, equally wild and beautiful, is in the Flathead Indian Reservation. The Mission Range is narrow and high. Peaks rise up to 10,000 feet and tower more than 6,000 feet above the Swan Valley to the east and the Mission Valley to the west. It is a very rugged range, having steep, deep, and narrow canyons. Small glaciers lie on several peaks. Mountain goats, grizzly and black bear, deer, elk, coyotes, mountain lions, and grouse are among the varied wildlife. Over 130 lakes provide a total of about 2,400 acres of water surface (fig. 2). Some lakes are barren; others offer good fishing. Streams generally are very rapid, often brush-choked, and usually provide poor fishing (fig. 3). The trail system is rather limited. Most of the trails are dead-end routes up the deep, east-west canyons to the high cirque lakes. North-south trails, loop trails, or trail connections from one drainage to the next are scarce. About half of the trails within the Primitive Area and almost all on the west side of the Mission Mountain Range are old Indian or packer trails, usually rough, steep, and unsigned. Campsites are not abundant, and horse feed is very scarce (fig. 4). There are about 20 access points, including six trails through passes from the Indian Reservation to the west.

Figure 2. - The Mission Range is narrow, but high and rugged. There are a few small glaciers and over 130 lakes. Turquoise Lake and Sunrise Glacier are shown here.

Figure 3. – The streams in the Mission Mountains are often beautiful cascades, such as this one above Glacier Lake, but they are usually too rapid and brush-choked to provide good fishing.

SAMPLE DESIGN

Sampling was concentrated on more heavily used trails. The trail to Glacier Lake, shown here, was by far the most popular. It accounted for close to half of all group visits. It was also the most heavily sampled trail.

The basic sample design was stratified sampling. This concentrated field time on trails having enough use to enable us to observe the registration behavior of visitors; thus we reduced the number of wasted sample days that didn't yield any data. Trail use was expected to have a highly skewed distribution--a few trails heavily used and many very lightly used. We also suspected that some types of trails might have different registration patterns at certain times.

Seven strata were established, differentiated on the basis of varying combinations of three variables: season (summer or fall), time of week (weekday or weekend), and expected use on trails (see table 1). Trails were placed in one of four classes of use on the basis of judgment estimates made by Forest Service Ranger District personnel. The four classes were 1/4 to 1 (very light), 1 to 2 (light), 2 to 5 (medium), or over 5 (heavy) visits per day, on the average. Trails estimated to average less than one-fourth of a visit per day were not included (table 1).

Two-day sampling units, rather than 1-day units, were used to reduce (a) the frequency of zero observations, (b) travel expense, and (c) variability in the estimation equations. The number of sample units allocated to each strata was based on the following: (a) The expectation that heavy-use strata would be more variable than light-use strata; (b) that interviewing costs would be much less in the heavy-use strata due to more visitor contacts per workday; and (c) that use estimates were desired for individual trails. We felt that 11 to 18 sampling units in each stratum would produce an adequate regression estimate for each trail even if the corresponding estimates of precision (the estimates of error terms) might be unreliable. Lightly used trails were intentionally sampled at a lower sampling intensity than believed desirable for statistical reasons because more intensive sampling would not have been economically feasible. The numbers of trails and 2-day sample units in each strata are shown in table 1.

Table 1.--*Definition of strata and sample selection*

Stratum number	Combination of variables				Allocation of sampling	
	Season[1]	Time of week	Estimated use	Trails	Total sample units	Sample units selected[2]
			Persons per day	*Number*	*Number*	*Number*
1	Summer	Weekend/ holiday	>5	1	14	12(86)
2	Summer	Weekdays	>5	1	26	12(46)
3	Summer	All days	2-5	1	40	14(35)
4	Summer	All days	1/4-2	16	340	18(5)
5	Fall	Weekend/ holiday	2-5	5	45	13(29)
6	Fall	Weekdays	1-5	9	207	30(15)
7	Fall	Weekend/ holiday	1/4-2	13	117	11(9)

[1]Summer season was from June 15 to September 2, inclusive. Fall season was from September 9 to November 11, inclusive. In general, the end of the season is determined by the onset of winter so that the November 11 date was known only after the season actually closed. The hunting season for mountain goats opened on September 15, and about 100 permits were issued. Most of the area opened for either sex elk hunting beginning September 21; the extreme northern part opened on October 27. Deer hunting opened October 27. Fishing was permitted during the entire study period.

[2] Sampling intensity in percent is shown in parentheses.

Sample Selection

Sample units were randomly selected within the constraints of feasible work scheduling. On weekdays, one location was sampled. On weekends and holidays, two locations were sampled. We selected 110 two-day sampling units (table 1): 56 units during the summer and 54 in the fall. First, dates were chosen randomly for each stratum, and then a trail location was randomly chosen for each date. Sample dates were chosen first for stratum 1, then for stratum 2, and so on from the remaining available workdays.

METHODS

An 18-mile round trip, much of it on snowshoes, was required to service this self-registration station at Elk Pass in late October.

The variables in each stratum were measured using a questionnaire for interviews with groups entering or leaving (fig. 5). Supplementary (covariate) information was obtained by establishing registration boxes on each trail, where entering groups could register by filling out a wilderness registration card (Appendix I). This was a condensed version of the questionnaire used for trail interviews. Mechanical counters placed on some of the most heavily used trails and access roads provided additional covariate data.

Interviewing Procedures

Four interviewers worked as two-man teams checking sample locations from 8 a.m. to 8 p.m. from June 15 until October 20. From October 20 through November 11 the checking period was shortened to 12 noon to 6 p.m. because the reduction in daylight hours coupled with changes in use lessened the chances for missing parties. This made it possible to check twice as many locations each day during the last 3 weeks--four locations on weekends, two on weekdays.

Interviewers stationed themselves up the trail, out of sight of the registration station. They drove personal cars rather than official Forest Service vehicles to avoid influencing visitor registration. Interviewers were dressed in official uniform. They conducted a brief interview with every party that entered or left.

Figure 5. – Brief interviews were conducted with every party entering or leaving during sample periods to establish actual use to compare and relate to registered use. Sampling was intensive; close to half of the 1968 visitors were contacted.

Registration Stations

Unmanned registration stations (fig. 6) were installed at 19 trail entrances (fig. 7) in early June, except for trails through the passes; snow made these inaccessible until late June and early July. The locations for these stations were selected in consultation with the Ranger District staff and included all trails thought to be used by at least an average of one group every 2 weeks (roughly equal to one-fourth of a visit per day). One additional trail meeting this criterion was discovered and added several weeks after the study began; it leads from the Indian Reservation south of the Primitive Area to Gray Wolf Lake. The registration stations were located where the trails began at the road, rather than on the Primitive Area boundary (except for trails through the passes).

Vandalism of unmanned registration boxes as well as of signs, counters, and other equipment was not a problem. However, two registration stations were severely damaged by porcupines. Several more stations suffered similar damage, although it was minor. After stovepipe was placed around posts supporting the signs and boxes, porcupines gave us no more trouble.

The registration box, sign, map on signboard, and card format that we used all were based on Wenger (1964).[2] The sign directed one person from each group to register for the entire party when entering. The registration card (Appendix I) asked for a

[2]The sign, however, following current Forest Service standards, was gray and brown instead of yellow and black as in Wenger's test.

Figure 6. - An estimated 65 percent of all groups registered in the Mission Mountains Primitive Area.

standard trip description: name, address, party size, date and time in, planned date and time out, number of pack and saddle animals, whether an outfitter or guide was used, number of people planning certain activities, the numbers of the "compartments" in which they planned to travel, and locations where they planned to camp if they were staying overnight. The registration card was accompanied by a folded map showing 27 numbered "travel compartments." The compartments were based on trail patterns, usually conforming to drainage basins. The lower and upper halves of drainages were generally divided into separate compartments.

Registration cards were collected on each sampling day and stapled to corresponding interview forms for punching. Registration boxes were serviced at least once each week, except those in the mountain passes, which were serviced either two or three times during the study.

Traffic Counters

Conventional nonprinting pneumatic traffic counters were installed on the access roads to the two most used trails: Glacier Lake (number 1 on fig. 7), and Cold Lake (number 2 on fig. 7). A pressure-pad adaptation of a similar traffic counter was installed on the Glacier Lake trail. Four prototype ultrasonic beam trail traffic counters were installed: two on the Glacier Lake trail; one on the Cold Lake Trail; and one on Fatty Creek trail (number 3 on fig. 7), which was the next most heavily used trail. Counters were read three times each day when the location was sampled, and every third or fourth day at other times.

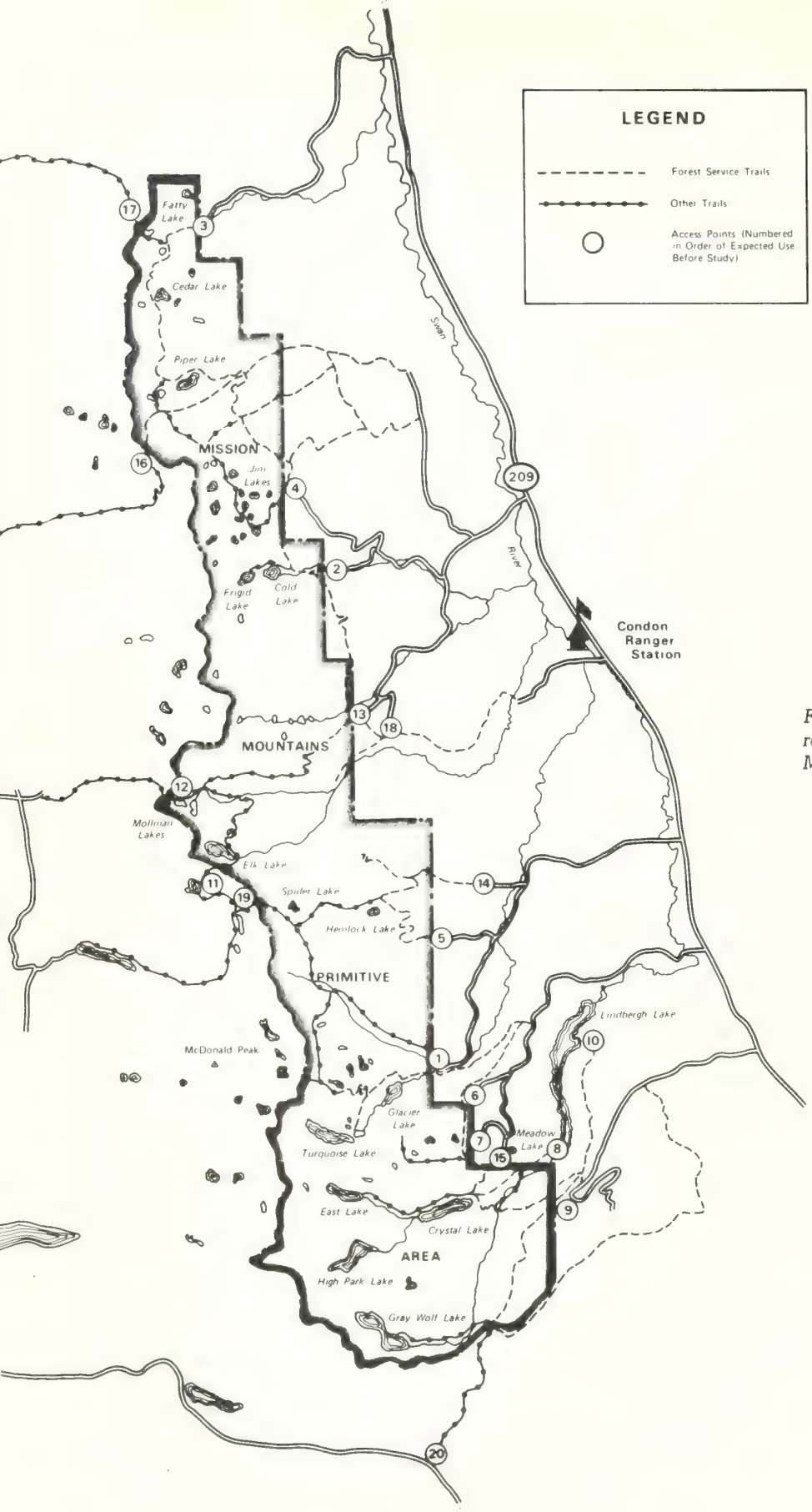

Figure 7. – Map showing access roads to trails on the Mission Mountains Primitive Area.

RESULTS

Only about 5 percent of the visitors traveled by horse, largely due to rough terrain and the scarcity of forage. Even fewer parties traveled with guides or outfitters.

Visitors responded well to the personal interview situation. There seemed to be no resentment or problem with visitors feeling "spied upon" concerning registration. No one refused to answer questions.

In total, 470 groups were interviewed, 312 of which were interviewed both when entering and when leaving. This produced a total of 782 interviews (table 2).

Registration Rates

A key question asked all interviewed groups was: "Did your party register upon entering the area?" Registration forms were checked to see if the answers to this question were truthful. In more than 95 percent of the cases, groups who had not registered admitted honestly that they had not.

An estimated 65 percent of all groups registered. This registration rate is fairly close to the 74-percent registration rate for the two wildernesses studied by Wenger and Gregersen (1964). Although the Mission Mountains Primitive Area is more than 500 miles from the area studied by Wenger and Gregersen and does not draw visitors from the same geographical region, both are predominantly day-use hiking areas that serve visitors largely from nearby regions rather than from the entire nation.

Table 2.--*Number of groups interviewed by stratum*

Stratum number	Entering only	Leaving only	Both entering and leaving	At least once
1	21	39	142	202
2	16	16	81	113
3	9	26	47	82
4	3	2	7	12
5	3	3	25	31
6	4	10	9	23
7	2	4	1	7
Totals	58	100	312	470

The registration rate was depressed by stratum 7 (fall weekends on lightly and moderately used trails) where only seven groups were contacted, none of whom had registered. Registration rates, by stratum, were:

	Estimated registration rate (Percent)	*Standard error*[3]
SUMMER		
Stratum		
1	69	2
2	76	4
3	68	6
4	83	20
FALL		
Stratum		
5	58	9
6	57	10
7	0	0
Summer strata pooled[3]	74	7
Fall strata pooled[3]	41	19
All strata pooled[3]	65	6

Use was even more heavily concentrated on a few trails than had been expected; as a result of this and the greater sampling intensity for heavy-use strata, 93 percent of all interviews occurred on two trails. Only five trails yielded five or

[3]A confidence interval of plus or minus one standard error around the estimated mean will contain the true mean about two-thirds of the time. Plus or minus 2 standard errors will contain the true mean about 95 percent of the time. See Appendix II for the formula (from Cochran, 1963, section 6.11) that was used to calculate standard errors.

more interviews. The registration rate and number of groups interviewed at least once are shown in the following tabulation for all trails on which at least one interview was obtained (see fig. 7 for trail locations).

Trail name and number		Registration rate (Percent)[4]	Number interviewed
Glacier Lake	1	71	346
Cold Lakes	2	67	89
Fatty Creek	3	73	5
Jim Lakes	4	22	4
Red Butte	5	100	2
Skylark Lake	7	0	1
S. Lindbergh Lake	8	50	4
Beaver Creek	9	87	5
Mollman Pass	12	100	1
S. Fork Cold Creek	13	33	6
Hemlock Creek	14	0	2
Meadow Lake	15	100	1
Elk Creek	18	32	4

Completeness of Response on Registration Cards

The key items on the registration card were completed by a high percentage of the registrants as shown in the following tabulation:

Item	Items completed (Percent)
Name and address (sufficient to address mail)	99
ZIP code	74
Date entered area	93
Time entered area	92
Date left area (planned)	78
Time left area (planned)	69
Number of persons in group	99
Number of saddle animals	[5]100
Number of pack animals	[5]100
Accompanied by guide ("yes" or "no" checked)	98
Travel compartment numbers (planned)	62
Campsite locations (planned)	[6]65
Activities (planned)	[7]10

[4]These are weighted means wherever the sample groups came from more than one stratum; thus four groups were contacted at Jim Lakes and the estimated registration rate is 22 percent, rather than 25, because of the weighting of the strata involved.

[5]Percentage of parties traveling with stock who indicated the number of animals.

[6]Tabulations are based only on those visitors staying overnight in the area.

[7]This question was apparently misunderstood. Instead of indicating the *number* of persons in each group who planned to participate in each of the activities listed, 73 percent indicated the activities that someone in the group planned to pursue. Seventeen percent did not answer.

Accuracy of Planned Length of Stay

Signs at registration stations directed visitors to register when entering. This meant that visitors could only indicate *expected* rather than *actual* time of departure. Many factors, such as adverse weather and unexpected trail conditions, upset visitors' time schedules. On the average, visitors who registered did not stay quite as long as they had expected. Visitors who did not register, but who were interviewed both upon entering and leaving, overestimated their stay by approximately 5 percent. About 61 percent of all registered groups who were interviewed upon exiting estimated the length of their visit correctly (when both the planned and actual stay were expressed to the nearest whole hour). Groups that came out earlier than planned made up 23 percent of the total, and parties that stayed longer than planned accounted for 16 percent. Generally, short stays (under 5 hours) were longer than expected, while longer visits tended to be shorter than planned. Expected length of stay exceeded actual length of stay by 10 percent for those registered groups who were interviewed upon exiting.

Relationships of Visitor Characteristics, Other Variables to Rates

All groups do not register; furthermore, certain types of visitors are less likely to register than others. Therefore, the raw registration data not only gives an incomplete picture of the use of an area but also a distorted view. Information such as the following on how a number of factors were related to registration rates could aid managers in interpreting registration data and also in planning ways to raise registration rates, which is an important management objective.

Sex and age.--Groups containing adult females generally registered at higher rates than did all-male or teenage groups (table 3). The groups that were made up entirely of adult males had an estimated registration rate (66 percent) about equal to the overall average. All of the types of groups containing teenage boys or girls had below-average rates (with the one exception of mixed adult and teenage females, in which case only two groups were interviewed and both had registered).

Size of group.--The medium-sized groups (3 to 5 members) had higher estimated registration rates than either the small or large groups (table 3). One-man groups (all one-person groups were male) had the lowest registration rate of all, but those who did register furnished more complete information than did larger groups. All one-person registrations contained complete addresses, 84 percent provided ZIP codes, and almost all gave date and time both in and out, travel compartment numbers, and planned campsites. Presumably, the lone individual who registers sees some possible security value in providing full information about his wilderness travel plans.

Length of stay.--Visitors who stayed overnight registered at a higher rate than visitors who did not (table 3). The shorter the stay, the less likely were visitors to register.

Place of residence.--Local residents (only 8 percent of all interviewed groups) had a slightly lower registration rate than visitors who lived outside the local area (table 3). There was no discernible difference in registration rates between Montana residents and out-of-State visitors.

Weather conditions.--Interviewers subjectively classified the weather conditions at the time of the interview, and the registration rates for entering parties were related to the weather (table 3). Data from exiting parties were not used because weather conditions at the time they would have registered could no longer be observed. Temperature had little effect on registration rates. Rain and snow, however, reduced registration rates substantially.

Table 3.--*Effect of certain visitor characteristics and other variables on registration rates*

Category	Estimated registration rate	Number of groups interviewed at least once
	Percent	
SEX AND ESTIMATED AGE		
All adult males (over 20)	66	141
All teenage[1] males	56	26
Mixed adult and teenage males	55	105
All adult females	100	2
All teenage females	0	1
Mixed adult and teenage females	100	2
All adult (male and female)	78	59
All teenage (male and female)	50	2
Mixed ages (mixed sexes)	81	131
SIZE OF GROUPS		
Small		
1	55	38
2	63	158
Medium		
3	72	95
4-5	72	120
Large		
6 or more	66	59
LENGTH OF STAY		
Overnight	74	69
Day-use	63	401
Day-use (5 or more hours)	69	230
Day-use (less than 5 hours)	55	171
RESIDENCE		
Local (within 60 miles)	61	36
Nonlocal (over 60 miles away)	65	434
Montana residents	65	369
Non-Montana residents	66	101
WEATHER CONDITIONS		
Temperature		
Cold	75	14
Cool	67	152
Warm	76	191
Hot	74	32
Clouds/precipitation		
Fair	70	168
Partly cloudy	75	112
Raining	55	31
Snowing	50	8

[1] Younger children are included with "teenagers."

Kind of activity.--Groups that hunted had a low rate--only an estimated 34 percent registered (based on 38 hunter groups interviewed at least once). Groups having members who fished had a 75-percent rate (based on 357 fishing groups interviewed at least once). Groups that neither fished nor hunted had an intermediate rate of 54 percent (based on 75 groups interviewed).

Prior use during the season.--Groups were asked if most of the people in the group had visited the area during 1968, prior to the interview. More than half had visited the area earlier during the season. Familiarity with the area from previous visits lowered rates by only a small amount; the first-time visitor groups had an estimated rate of 69 percent (201 interviews), whereas groups that had made earlier visits had a 64-percent rate (269 interviews).

Mode of travel.--Horsemen registered at a lower rate than hikers--an estimated 44 percent for horsemen compared to 66 percent for hikers. However, the horseman sample consisted of only 9 groups interviewed (against 461 hiker groups); thus, neither the horseman rate nor the difference between the two rates can be estimated precisely.

Use of outfitters or guides.--The sample of groups that used outfitters or guides included only 5 groups, only one of which registered. In contrast, an estimated 68 percent of the groups without outfitters or guides registered.

Time of week.--Weekday registration rates were estimated at 72 percent (157 interviews). Weekend and holiday rates were lower, 62 percent (313 interviews).

Reasons for Not Registering

About 32 percent[8] of the 470 groups who were interviewed did not register. These groups were asked by interviewers *why* they had not registered to try to learn if there is some way to raise registration rates. A tabulation of their replies follows:

Reasons for failing to register	*Nonregistrants* (percent)
In a hurry, did not want to take time	21
Planned to register on way out	12
Had registered on a previous visit, thought once per season was all that was required	8
Only going a short distance, did not think it necessary to register	6
Did not notice registration box and sign; in some cases because of darkness	5
Did not like to register	4
Said they had registered, but had not	4
Raining	2
Thought someone else in party had registered	2
Miscellaneous reasons	28
No reason given	8

[8]Proportion of interviewed people who registered (68 percent) is higher than the estimated overall registration rate (65 percent) because the latter is a weighted average. Rates were below average in some lightly sampled strata and high in some heavily sampled strata, accounting for the discrepancy between raw and weighted figures.

LUCAS, ROBERT C., SCHREUDER, HANS T. and JAMES, GEORGE A.

1971. Wilderness use estimation: a pilot test of sampling procedures on the Mission Mountains Primitive Area, USDA Forest Serv. Res. Pap. INT-109, 44 p., illus.

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So little time was required to register that perhaps those unwilling to take the time didn't understand the importance of registering.

The field interviewers were convinced that at least a majority of the people who said they planned to register when leaving were telling the truth, rather than rationalizing. If this is the case, then the registration rates reported above might be consistently 2 or 3 percentage points low.

The people who said they did not see the box (5 percent) were also probably truthful. We watched several people, usually bent over with heavy packs, walk within 5 feet of the registration station without seeming to notice it at all.

Comparison With Results of Previous Studies

Many of our findings can be compared quite directly to those reported by Wenger and Gregersen (1964) (see table 2). Very few comparisons with the results reported by Thorsell (1968) are possible, except for those dealing with registration rates (about twice as high in the Mission Mountains Primitive Area) and variations in such rates from trail to trail, (which were less in our study). Comparisons are important because they suggest the degree to which the same factors influence registrations in the same ways in different wildernesses, and they indicate whether the same use-estimating formula could be applied in different areas.

Although Wenger and Gregersen did not publish confidence intervals for their estimates, it seems unlikely that the difference between the overall registration rates in the Oregon study and in our study is statistically significant. The information visitors provided as to their addresses, times of entry and departure, and group sizes was slightly more complete in our study than that reported in the Oregon study.

Most factors seem to influence registration rates in the Oregon study as well as in our study, although usually to a lesser degree in our study. However, the effects of two factors--fishing and the time of the week--were reversed. Unfortunately, the fishing classification was the one factor that was not defined in the same way in the two studies. In Oregon, visitor groups were classified as "fishermen" only if the specific purpose of the trip was fishing for the entire group. In Montana, they were classified as "fishermen" if some of the group fished or planned to fish.

Many beautiful lakes, such as High Park Lake pictured here, were lightly used, apparently because of poor access due to distance or lack of trails.

GENERATION OF USE ESTIMATES

Regression estimates of use were not improved by adding information on one- and two-person and local groups.

The basic data from which use estimates were generated included information obtained from registration cards completed by visitors entering the area (called X variables); personal interviews on sampling days with entering visitors after they had had an opportunity to register at the registration stations (Y variables); and personal interviews on sampling days with visitors leaving the area (Z variables). Several analytical estimation procedures were tested to determine which one produced the most precise estimates of use including: (a) registration information, (b) ratio estimation, (c) stratified random-sampling estimation, and (d) simple and multiple regression estimation.

The target (or planned) population we wanted to estimate included all visitors to the Mission Mountains Primitive Area. However, the sampled populations on which analyses were based were slightly different from this target population because we didn't sample: (a) The few winter and spring visitors, (b) users of lightly used and unknown trails, (c) visitors who did not enter on established trails, and (d) users who entered and left on sampling days during late evening and early morning hours (from 8 p.m. to 8 a.m.). Some indication of the effect of our decision not to sample during these hours is the fact that about 11 percent more groups were interviewed upon leaving than upon entering (412 vs. 370 groups). This was due primarily to early entry of visitors into the area. A few groups probably entered so early and left so late that they were missed entirely. In addition, some uses such as total use in visitor-days were estimated in terms of how long people *expected* to stay rather than how much time they *actually* spent in the area.

Estimates of use were generated for 13 variables (see Appendix III), only three of which developed as variables of primary importance. These three (called *key* variables throughout this report) are (a) number of visitors (i = 1), (b) use in

visitor-days (i = 6), and (c) number of groups (i = 7). Other variables--number of riding groups, saddle animals, pack animals, and so forth--were of secondary importance because almost all use of the wilderness was by hikers.

The relative strengths and weaknesses of each of the use-estimation procedures are discussed along with the estimates derived on pages 24-34.

Registration Station Data

A box containing registration forms together with a sign requesting each entering group to register is the least expensive technique for obtaining information about wilderness users. Used alone, however, it cannot provide reliable estimates of recreation use, mainly because of nonregistration by some groups. At best, the method can provide *lower* bounds to estimated use. It can tell an administrator that an area is receiving *at least* as much use as the registration totals indicate, assuming (a) that entering groups furnish reasonably accurate answers to all questions, and (b) that there is little stuffing of registration boxes with falsely completed forms. These seemed to be safe assumptions. Information derived from uptrail interviews confirmed the accuracy of answers on registration cards and also revealed that only two groups out of 470 "stuffed" the boxes.

Information from all completed registration forms was added to produce raw, uncorrected estimates of use by strata, for all variables (see table 4 for key variables and table 10, Appendix III, for all variables).

Table 4.--*Estimates of recreation use on the Mission Mountains Primitive Area, Montana, based on raw (uncorrected) registration information, summer-fall, 1968*

Strata	Visits	Total use	Groups
	Number	*Visitor-hours*[1]	*Number*
Summer	2,705	30,265	680
Fall	354	4,527	130
Summer + Fall	3,059	34,792	810
1	658	6,511	166
2	597	4,533	169
3	570	3,932	137
4	880	15,289	208
5	140	1,397	51
6	136	2,375	53
7	78	755	26

[1]Divide visitor-hours by 12 to get visitor-days, as defined for federal recreation area statistics.

Ratio Estimation (Corrected Registration Information)

To generate more accurate estimates of use from raw data computed from completed registration forms, the data can be corrected using an expansion factor based on the estimated registration rate; in statistical terms, this provides a ratio estimate.[9] Estimates of use with their associated standard errors, corrected for registration rate, are shown in table 5 for the key variables.

Raw registration totals were multiplied by the following correction factors: number of visits, 1.35; number of visitor-hours, 1.63; and number of groups, 1.24.

Table 5.--*Estimates of recreation use on the Mission Mountains Primitive Area, Montana, based on ratio estimation (corrected registration information), summer-fall, 1968*

Strata	Visits		Total use		Group	
	Estimate	Standard error[1]	Estimate	Standard error[1]	Estimate	Standard error[1]
	Number	*Percent*	*Hours*	*Percent*	*Number*	*Percent*
Summer	3,652	6.3	49,332	14.7	843	8.1
Fall	478	do.	7,379	do.	161	do.
Summer + Fall	4,130	do.	56,711	do.	1,004	do.
1	888	do.	10,613	do.	206	do.
2	806	do.	7,389	do.	210	do.
3	770	do.	6,409	do.	170	do.
4	1,188	do.	24,921	do.	258	do.
5	189	do.	2,277	do.	63	do.
6	184	do.	3,871	do.	66	do.
7	105	do.	1,231	do.	32	do.

[1]Standard error, expressed as percentage of the estimate. Standard errors do not vary from stratum to stratum because in ratio estimation variance is unconditional.

[9]We used the "combined ratio estimate" from Cochran (1963, section 6.11).

Ratio estimates also have advantages from a statistical standpoint. The ratio estimates had the smallest error terms of any of the estimation methods tested. A ratio estimate is based on an assumption of linearity through the origin--in other words, when there are no registrations, there would be no estimated use (Cochran 1963, section 6.9). This assumption fits well. We observed use only for 12 hours on each of the 2 days in a sample unit, while registered use was measured over the whole 48-hour period. This means registered use could be either larger or smaller than observed use. If use and registration were measured over identical time periods, actual use could not be less than registered use. This difference could introduce a bias, probably small.

Ratio estimation is also best if the variance of Y at a given value of X is proportional to the value of X--in other words, if the variance of Y increases as X increases. This also seems reasonable for trail registration data.

In practical terms, ratio estimation is easy for land managers to understand and apply. The procedure is intuitively obvious and the calculations are very simple.

Stratified Random-Sampling Estimation

Unbiased estimates of use with their associated standard errors were generated using stratified random-sampling estimation procedures (table 6). Two sets of estimates were produced: one based on data from persons interviewed when entering, the other based on persons interviewed when leaving. These data were multiplied by the inverse of the sampling fraction. For example, 12 of 14 possible 2-day units were sampled in stratum 1, so the interview totals were multiplied by 14/12 or 1.1667.

The estimates of the number of visits and number of groups entering and leaving were about the same in the summer, but were markedly different in the fall. This was attributed to the fact that visitors who entered the area prior to the arrival of the interviewer at 8 a.m. (or at 12 noon the last few weeks) were more common in the fall than in the summer.

Expected and actual hours of use were quite similar in the summer, but expected use (12,996 hours) far exceeded actual use (3,681 hours) in the fall. This was partly attributed to the fact that unplanned factors reduced actual length of stay in the fall about 10 percent below visitors' expectations. However, most of the difference between expected and actual hours of use in the fall was attributed to sampling variability in stratum 7 (one group that planned to stay 8 days--an unusually long time--was interviewed only upon entering). The precision of total estimated summer visitor-hours was high for both entering and exiting visitors, but was unacceptably low for total estimated fall visitor-hours. More precise estimates for the three key variables were obtained by combining summer and fall strata.

Sampling to obtain estimates of use was far less efficient in the fall than in the summer. This probably reflected the light and variable use in the fall. It is also more difficult to select hours in the fall for interviewing that would assure contacting nearly all visitors at least once. Some hunters enter early in the day, a few leave late.

This type of estimation did not give adequate precision at reasonable cost. Sampling intensities during summer, fall, and summer+fall were high (13, 15, and 14 percent, respectively) as were costs; yet precision levels for several variables were considerably less than desired. One advantage of this method is that unbiased estimates and precision levels are obtained for all variables of interest.

Where highly reliable estimates are obtained for several variables, as was the case for some strata in this study, they can be used as a standard for comparison with estimates from other estimation methods. These other methods might be more efficient,

but they depend on certain assumptions that cannot be adequately tested. Such a comparison would only have validity if "loopholes" were closed, such as the visitors who entered or left on sample days when the interviewers were not on the trail. Otherwise the sampling fraction, based on the proportion of *days* sampled, exaggerates the proportion of *use* sampled. One way of dealing with this problem would be to define the sampling frame in terms of hours, and choose blocks of hours randomly. The extremely late and early hours, say from 11:00 p.m. to 5:00 a.m., could probably be safely ignored

Table 6.--*Stratified random-sampling estimates of recreation use on the Mission Mountains Primitive Area, Montana, based on interview of entering and leaving visitors, summer-fall 1968*

Stratum	Visits		Total use		Groups	
	Estimate	Standard error[1]	Estimate	Standard error[1]	Estimate	Standard error[1]
	Number	*Percent*	*Visitor-hours*	*Percent*		*Percent*
BASED ON INTERVIEW OF VISITORS UPON ENTRANCE						
Summer	2,878	11.3	20,918	12.9	748	10.3
Fall	506	22.9	12,996	59.8	209	18.9
Summer + Fall	3,384	10.6	33,914	24.3	957	9.0
1	763	6.8	6,795	13.2	190	5.8
2	692	11.3	5,619	17.6	200	8.6
3	686	16.9	3,774	23.7	160	17.5
4	730	41.5	4,730	46.0	189	36.0
5	228	37.7	958	26.3	97	[illegible]
6	200	31.0	4,039	44.6	83	25.3
7	78	60.3	8,154	92.7	29	41.4
BASED ON INTERVIEW OF VISITORS UPON DEPARTURE						
Summer	2,898	12.1	22,275	8.0	776	9.6
Fall	668	20.4	3,681	25.0	273	19.3
Summer + Fall	3,566	10.6	25,956	7.8	1,049	8.7
1	838	6.8	8,038	9.9	209	5.6
2	600	13.8	4,125	11.5	191	10.5
3	837	16.7	7,281	14.8	206	16.9
4	623	49.1	2,832	38.4	170	56.0
5	215	40.0	652	37.3	90	38.2
6	297	22.2	2,279	35.4	131	22.1
7	156	52.6	750	49.9	49	52.5

[1]Standard error, expressed as percentage of the estimate.

Regression Estimation

Estimates of use and associated standard errors were generated for the three key variables using simple linear regression estimation procedures. The three basic regression equations used in this analysis expressed linear functions of the corresponding covariate.

The precision of total estimated summer use was high for all three key variables, but unacceptably low for all fall-use estimates (table 7). The reasons for the large standard error terms for all variables in the fall cannot be determined precisely. Sampling intensity should have been adequate with a 29-, 14-, and 9-percent sampling rate, respectively, in strata 5, 6, and 7. A zero registration rate likely accounted for the low precision level in stratum 7, yet registration rates of 58 and 57 percent were obtained for strata 5 and 6, respectively. The high standard errors may be a function of the greater inherent variability of fall use and registration rates. The average length of stay was a little longer during the fall than it was during summer, but it was much more variable. Such use included (a) a mixture of deer and elk hunters walking the lower elevation trails for a few hours, (b) fishermen and hikers out for the day, and (c) mountain goat hunters camping for days in the high country.

Summer and fall strata were pooled to generate season-long estimates of use for the key variables using simple linear regression estimation methods (table 8). The advantage of pooling all strata, of course, is the large sample size obtained (n = 110 2-day sample units). Fairly precise season-long estimates of use were obtained for all variables. Pooling all strata can, of course, yield misleading results if some of the strata are substantially different populations.

Table 7.--*Regression estimates of recreation use on the Mission Mountains Primitive Area, Montana, based on self-registration--interview relationships, summer-fall, 1968*

Stratum	Visits		Total use		Groups	
	Estimate	Standard error[1]	Estimate	Standard error[1]	Estimate	Standard error[1]
	Number	*Percent*	*Visitor-hours*	*Percent*	*Number*	*Percent*
Summer	3,622	8.9	39,544	13.9	910	10.0
Fall	634	49.0	8,046	59.8	220	36.7
Summer + Fall	4,256	10.4	47,590	17.7	1,130	13.7
1	836	4.2	7,976	7.1	208	5.3
2	765	5.5	5,666	12.0	214	6.1
3	739	7.2	5,036	17.0	176	8.5
4	1,282	22.3	20,866	21.3	312	23.7
5	199	28.6	2,004	48.0	70	22.8
6	277	68.2	4,314	102.5	99	49.5
7	158	72.8	1,728	112.4	51	59.0

[1]Standard error, expressed as percentage of the estimate.

Table 8.--*Regression equations, coefficients of determination (R^2), and standard errors for the key variables*

Variable	Regression equation	Coefficient of determination (R^2)	Standard error
Season-long number of visits	$Y_1 = 0.51 + 1.26(X_1)$	0.88	7.02
Season-long recreation use (hours)	$Y_6 = 6.96 + 1.21(X_6)$	0.79	118.65
Season-long number of groups	$Y_7 = 0.16 + 1.24(X_7)$	0.86	1.97

where: X_1 = registration total for individual visits,

X_6 = registration total for expected hours of use,

X_7 = registration total for group visits.

Multiple regression analyses were next run to determine whether additional covariate information might result in more precise estimates of use, especially for the fall strata. Variables representing one- and two-person groups and local groups were added as covariates. These additional covariates were included because earlier work by Wenger and Gregersen (1964) indicated that small groups and local groups tended to register at lower rates than other groups. Results indicated that although the data for these types of use based on interviews generally improved precision as measured by the standard error of estimate, substitution of registration data for interview data essentially wiped out this improvement. Estimating procedures using interview data don't seem practical because an administrator would ordinarily have to work with registration data.

Regressions were also run to determine whether numbers of registered users might also give an adequate estimate of hours of use and number of groups. It was found that registered visits could be used as well as registered groups in the prediction of total number of groups, but the registered visits variable was considerably poorer than registered visitor-hours in the prediction of total visitor-hours.

Mechanical Counters

Mechanical counters were used in conjunction with interview information to evaluate devices that might be used for a several-year period following calibration to obtain inexpensive and acceptably accurate estimates of use. The study was concerned mainly with evaluating counting devices, rather than attempting to establish prediction equations based on their results.

Table 9.--*Regression equations, coefficients of determination (R^2), and standard errors for the key variables, based on mechanical counter relationships*

Variable	Regression equation	Coefficient of determination (R^2)	Standard error
	VEHICLE TRAFFIC-COUNTER REGRESSION		
Season-long number of visits	Y1 = -3.63 + 1.29 (TC)	0.67	17.68
Season-long recreation use (hours)	Y6 = -1,596.40 + 148.79 (TC)	.37	3,855.29
Season-long number of groups	Y7 = 0.47 + 0.29 (TC)	.66	4.16
n = 22			
	TRAIL PRESSURE-PAD COUNTER REGRESSION		
Season-long number of visits	Y1 = 9.33 + 0.84 (PC)	.83	14.85
Season-long recreation use (hours)	Y6 = 2.12 + 104.21 (PC)	.48	4,145.85
Season-long number of groups	Y7 = 5.20 + 0.16 (PC)	.69	4.00
n = 14			

The prototype ultrasonic beam counters could not be kept in adjustment and operating long enough to yield any usable counts. The counters operated well when tested indoors, but failed in the field, probably due to temperature fluctuations and moisture. The trail pressure-pad counter and traffic counters worked quite satisfactorily, however, and yielded useful information.

The regression equations expressed interview information obtained from entering visitors for the three key variables as linear functions of the corresponding pressure-pad counter (P.C.) and traffic counter (T.C.) covariate values (table 9). The analysis revealed that trail pressure-pad counters and vehicular traffic counters hold promise in estimating number of persons and number of groups, but that mechanical counters were essentially useless in estimating total visitor-hours. The single trail pressure-pad counter provided more precise estimates of number of persons and groups than did vehicular traffic counters on two access roads. However, both types of counters were inferior to registration boxes in estimating use.

Summary of Use Estimates

A summary of use estimates for key variables, based on results of ratio estimation is shown below for the Mission Mountains Primitive Area for the period June 15 to November 11, 1968, inclusive:

Variable	*Estimate*	*Standard error*[10] *(Percent)*
Total season-long visits	4,130	6.3
Number of summer visits	3,652	6.3
Number of fall visits	478	6.3
Total season-long group visits	1,004	8.1
Number of summer group visits	843	8.1
Number of fall group visits	161	8.1
Total season-long visitor-hours	56,711	14.7
Total season-long visitor-days[11]	4,726	14.7
Summer visitor-hours	49,332	14.7
Summer visitor-days[11]	4,111	14.7
Fall visitor-hours	7,379	14.7
Fall visitor-days[11]	615	14.7

The average length of stay was about 14 hours, and the average group size was 4.1 persons. Over 80 percent of all groups left the wilderness the same day they entered. Such a short average stay is much less than generally expected by recreation planners and managers for wilderness users, but it agrees with the results of studies in Oregon by Wenger (1964) and in the Boundary Waters Canoe Area by Lucas (1964). Another study in three Oregon and Washington wildernesses (Hendee et al. 1968) shows stays averaging only 2.2 to 3.0 days.

More than 94 percent of the visitors were estimated to be hikers. Most of the very limited horse use occurred in the fall. Hikers accounted for 97 percent of the summer use and 85 percent of the fall use. Only one user in a hundred was estimated to have employed guides or outfitters.

Use was distributed very unevenly throughout the Mission Mountains Primitive Area. This agrees with all previous studies of wilderness use. The estimated season-long distribution of use is shown in figure 8. Forty-four percent of all groups entered the area along the Glacier Lake Trail. Another 18 percent entered along the Cold Lakes Trail. Lakes appeared to be the major attraction, but use was appreciable only where there were trails leading to them. Some large lakes were lightly used, apparently because of long distances involved or because of lack of trails to them. Use dropped rather quickly as distance from access points increased.

This use distribution was rather different than the prestudy trail use estimates made by the administrators of the area for planning stratification. The summer pattern was more extreme; a few places were more heavily used than estimated, and a great many were more lightly used. In the fall, Glacier Lake was used more heavily than had been estimated on weekends, but almost all other locations were used less than expected.

---

[10]Standard error, expressed as percentage of the estimate.

[11]A visitor-day is defined as a recreation use that aggregates 12 person-hours. It might entail one person for 12 hours, 12 persons for 1 hour, or any equivalent combination of individuals or group use, either continuous or intermittent.

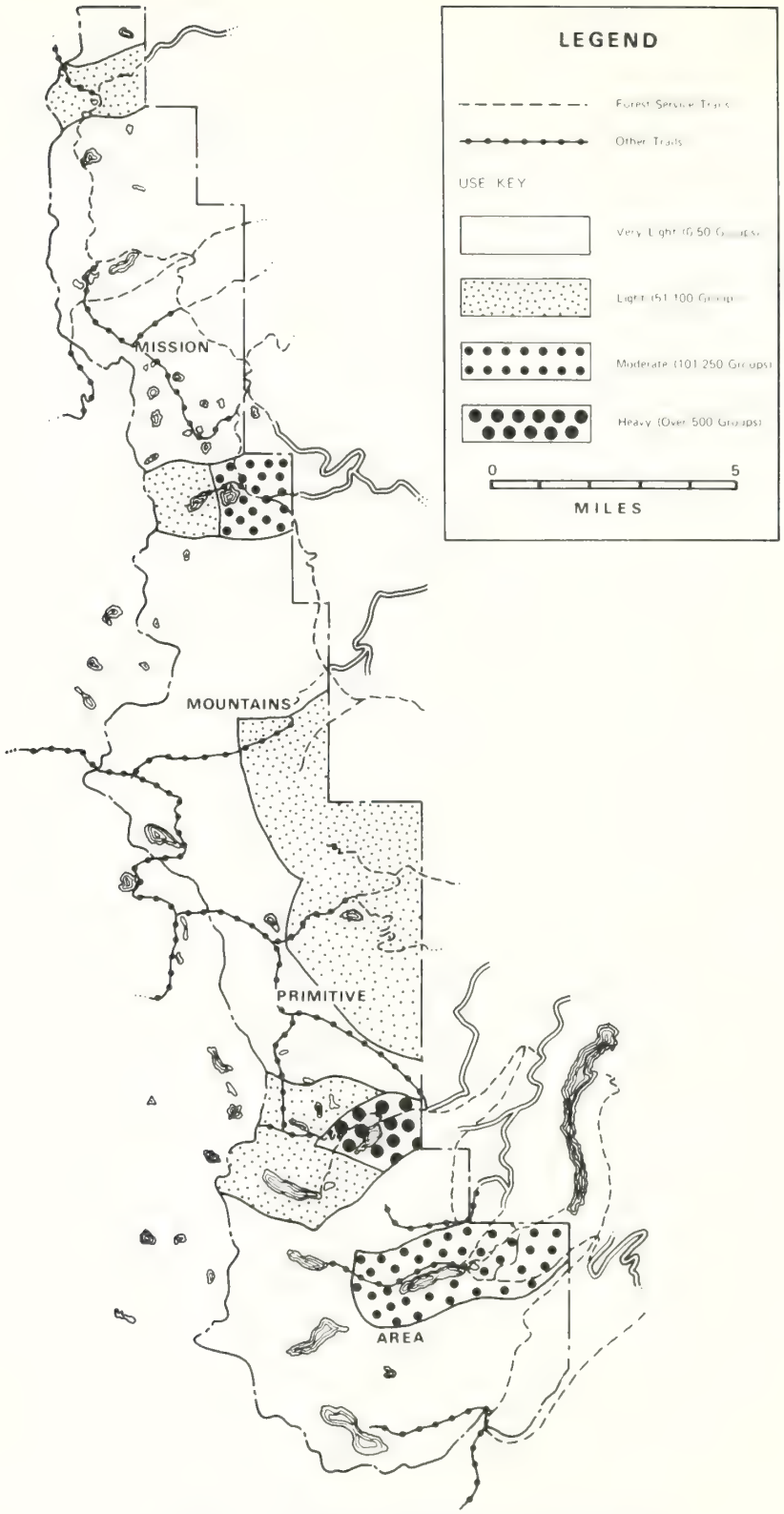

Figure 8. – Map showing season-long distribution of estimated use on the Mission Mountains Primitive Area.

Seventy-eight percent of all interviewed groups were residents of Montana, 92 percent of whom lived more than 60 miles from the Missions. Origin for out-of-State visitors follows:

	Percent of total use
California	3
Minnesota	2
Washington	2
Illinois	1
Iowa	1
Oregon	1
Wisconsin	1
Michigan, Indiana, Ohio, Kentucky	3
Northeastern States	3
Rocky Mountain & Intermountain States	1
Southeastern States	1
Nebraska, Kansas, Missouri	1

Four parties from Europe visited the area during 1968.

Fishing was the major activity in terms of time spent, accounting for an estimated 38 percent of all visitor-hours reported by parties leaving the area. Hiking was second, accounting for 26 percent; followed by camping, 16 percent; hunting, 10 percent; nature study, 3 percent; and miscellaneous activities, approximately 7 percent. Mountain climbing accounted for only 1/2 of 1 percent of total visitor-hours.

In summary, the Mission Mountains Primitive Area appears to be predominantly a summer, hiking, day-use wilderness. Use is distributed very unevenly within the area. It enjoys a largely regional clientele, but vacationists from all over the United States visit the area.

Cost of Using Same Estimation Technique

What might it cost to use the same estimation technique in the future? Cost of the pilot study was $11,500 for all field-sampling phases; approximately $1,500 for analyses and report preparation. A breakdown follows:

Interviewer salaries	$7,700
Training and supervision	600
Mileage and per diem	1,500
Equipment and installation (registration boxes, signs, forms, mechanical counters)	700
Study plan preparation	1,000
Data analysis and report preparation	1,500
Total	$13,000

The field-sampling cost ($11,500) can be prorated over several years because of relatively strong relationships between registration and interview information. Assuming that relationships between use and registration information remain constant,

estimates of use can be updated annually for perhaps 3 to 4 years based on self-registration information only, without interviewing entering visitors. It would be necessary only to solve the regression equation or apply the ratio estimate "correction factors" using registration information obtained each year. Thus, the average annual cost would amount to approximately $3,000, including about $300 annually for servicing registration stations, travel, and administration, which managers would probably have to spend anyway. The same registration system should continue in use for the period of time that use estimates are updated in this manner.

DISCUSSION/ RECOMMENDATIONS

Station placement is critical to achieve a high registration rate.

The study resulted in the development of a useful sampling tool for estimating current recreation use. This "tool" provides a means of updating use estimates for several years following field sampling. However, the sampling model is not recommended for general use because of high costs and certain weaknesses that must yet be corrected. The study yielded information that should make it possible to substantially reduce costs and improve sampling efficiency in future studies.

Sample Design

Sampling costs can be minimized by sound selection of sample size and allocation of sampling effort. Depending upon the characteristics of the population to be sampled, stratification may result in a gain in precision of estimates. However, stratification is unnecessary and complicates calculations where the population is homogeneous.

The most serious weakness in our sampling model was in the allocation of sampling effort. The sampling effort was subjectively allocated disproportionately between strata, but the analysis revealed that sample allocation was not optimum. In terms of maximum sampling efficiency and precision of estimates, some strata were sampled too heavily while other strata were not sampled heavily enough. Sampling effort should have been concentrated in the moderate-to-heavy-use strata, and little or no sampling should have been done in the light-use strata.

Each group interview on lightly used trails cost approximately $100, compared to a cost of only $5 per interview on heavily used trails, because few interviews were obtained per sampling unit. For example, stratum 4 (containing many lightly used trails) yielded only 12 interviews during 36 days of interviewing; stratum 7 yielded only 7 interviews during 22 days of interviewing. The least-used third of all trails yielded less than 5 percent of all registrations. Deletion of these trails from the sampling frame would have resulted in only a slight loss in the precision of estimates and would have cut sampling costs almost in half. Use of lightly used trails could have been adequately estimated by means of registration stations only, without employing uptrail interviewing.

Elimination of all lightly used trails from the sampling frame would have meant that the large, highly stratified sample would not have been necessary. Relationships between registration data and actual use were fairly similar from trail to trail; variation was small enough that strata representing different trails, seasons, and time of week could be pooled without significant loss of precision of the estimates. Considerably less than the 110 sampling units used in the study would have been expected to yield use estimates of acceptable precision.

A presampling method is needed to determine optimum stratification and to identify lightly used trails. Installing registration stations on all trails 1 year prior to field sampling would likely provide a satisfactory screening method. Although all entering groups do not register, the completed registration forms would indicate the relative magnitude of use on each trail.

Best Estimation Procedures

Both linear regression and ratio estimate (correction factor) procedures yielded acceptably accurate estimates. However, the ratio estimates were somewhat more precise (had smaller error terms), and would generally be easier for administrators to apply.

Extension of Results to Other Wildernesses

The prediction equations or correction factors generated in this study are not applicable to other unsampled wildernesses. Yet, our results were quite similar to those obtained by Wenger and Gregersen on the Three Sisters and Mountain Lakes Wildernesses in Oregon. The similarity in registration-use relationships for these three areas suggests that more economical ways of estimating use and establishing relationships between use and registration might be found. It is possible that particular types of wildernesses might have similar registration rates and use patterns. Other day-use hiking areas might also prove to be fairly similar. If further studies confirm this hypothesis, it might be possible to sample registration responses at one wilderness area only enough to confirm an expectation based on the type of wilderness involved.

Furthermore, it might also turn out that relationships change little over time. The general similarity in use patterns on the Mission Mountains Primitive Area, which was sampled during 1968, and the Oregon wildernesses, which were sampled 6 and 7 years earlier, indicates relative stability over time. If so, estimating equations might be used for rather long periods of time, perhaps 5 years or more, and only require limited periodic checking to detect any shifts with time.

Personal Interviews and Automatic Counters

The largest cost item in this and earlier studies was personal interviewing, which accounted for approximately 75 percent of the total sampling cost. Therefore, we should seek to eliminate or reduce the need for interviewing by devising some substitute methods, such as mechanical or electrical counters or automatic cameras. Although

trail and vehicular traffic counters yielded use estimates in our study that were not as precise as those obtained using regression and correction-factor estimation techniques, our tests using the counters are encouraging.

Development and testing of improved trail counting devices are needed and recommended. Directional, printout counters, that would record time and direction of movement as well as distinguish between hikers and animals (domestic stock and big game), would be particularly valuable. However, counters must be used in conjunction with other techniques, such as registration stations, for collecting information about the trail user because counters provide only simple counts of passing objects and would be useless for obtaining such information as length of stay. Automatic cameras could provide much more data than counters, but a registration system appears to be essential for obtaining descriptive information, such as length of stay,residence of visitors,etc.

Raising Registration Rates

More precise use estimates can be expected if the rate of registration can be raised. The main underlying reason for not registering appears to be a misunderstanding by users of the importance of registration information to wilderness management and a failure to see any personal advantage to registration. Registration seems to be perceived by many as a casual, voluntary activity. An educational and informational program to "sell" wilderness users on the need for registering seems needed. The management value and personal safety advantage of registering might be stressed in the message on signs; in map brochures made available for each area; in personal contacts with outdoor clubs and outfitters; in newspapers, and outdoor and conservation magazines; and in conservation education programs.

The optimum solution to increasing registration rates probably would be to make registration mandatory. A registration system would provide the information necessary for improving wilderness planning and management--enough, we feel, to offset any slight inconvenience for visitors it might produce. The Boundary Waters Canoe Area has had mandatory registration for several years, and the Forest Service began requiring registration in National Forest Wildernesses in California during the 1971 season.

Improvements in location and placement of registration stations and signs should be made, particularly if registration remains voluntary. The subdued gray and brown colors of stations and signs used during 1968 did little to attract attention. These standard Forest Service sign colors were intended to harmonize with the forest environment, but they might have harmonized *too* successfully! Wenger (1964) used more conspicuous yellow and black signs and obtained higher registration rates. In addition, the usual trailhead cluster of three sets of signs on three posts--registration box and sign, trail information sign, and "U-6" regulations prohibiting motor vehicles--probably detracted attention from the registration station. Placing the registration station and sign at some distance from the other signs, and very close to the trail, might be expected to attract more attention.

The effect on registration rates of placing stations at the wilderness boundary rather than at the trailhead cannot be estimated from our data. The registration rate might increase in situations where a fairly long trip is required to reach the boundary and the registration station, especially where the station is at a viewpoint after a steep climb, where many people might welcome an excuse to stop and rest awhile. On the other hand, a station located only a mile or two up a trail might produce a lower rate than a trailhead location, especially for horsemen. Placement of hitch racks at registration stations might encourage higher registration by horsemen.

Simplicity in the registration form probably is also a key to higher response rates. The registration form should be short and clear. The bare minimum of essential information is all that should be asked for. More detailed information can be obtained when and where needed using inexpensive mail surveys. Much of the information that might be desired, such as route followed, campsites used, activities engaged in, fish caught, or game shot can only be accurately obtained after the trip has been completed. More is lost by driving down registration rates with excessive demands for detail than this detail is worth.

Registration Systems

Whatever form the ultimate sampling model might take, a registration system seems worthwhile as one of the ingredients for wilderness use estimation. It offers better use figures than crude estimates and intuition might provide. Registration information provides detailed information about the forest user, and provides lower bounds for all variables of interest. Registration information can be expected to provide needed insurance if it develops after field sampling that the prediction equations prove to be no longer valid because of changed visitor-use patterns, registration response, or for other reasons. Self-registration also has a number of other advantages besides providing information to managers. It provides a chance to inform visitors of wilderness rules and regulations. It could be a valuable key to the control or redistribution of use within an area. It could prove useful in emergencies. A good registration system could convey to visitors an impression that the managing agency has a serious, professional concern for the wilderness resource and for the visitors.

Registration data can be of direct value for wilderness research as well as providing a source of sample lists of group leaders for mail questionnaires.

There is universal agreement on the need for improved wilderness management. Good estimates of wilderness use and a better understanding of wilderness users are essential for better management. Therefore, it appears highly desirable that wilderness managers move toward a uniform, comprehensive registration system for wilderness visitors. In addition, continuing effort to improve sampling techniques for obtaining accurate and inexpensive wilderness use estimates is clearly warranted.

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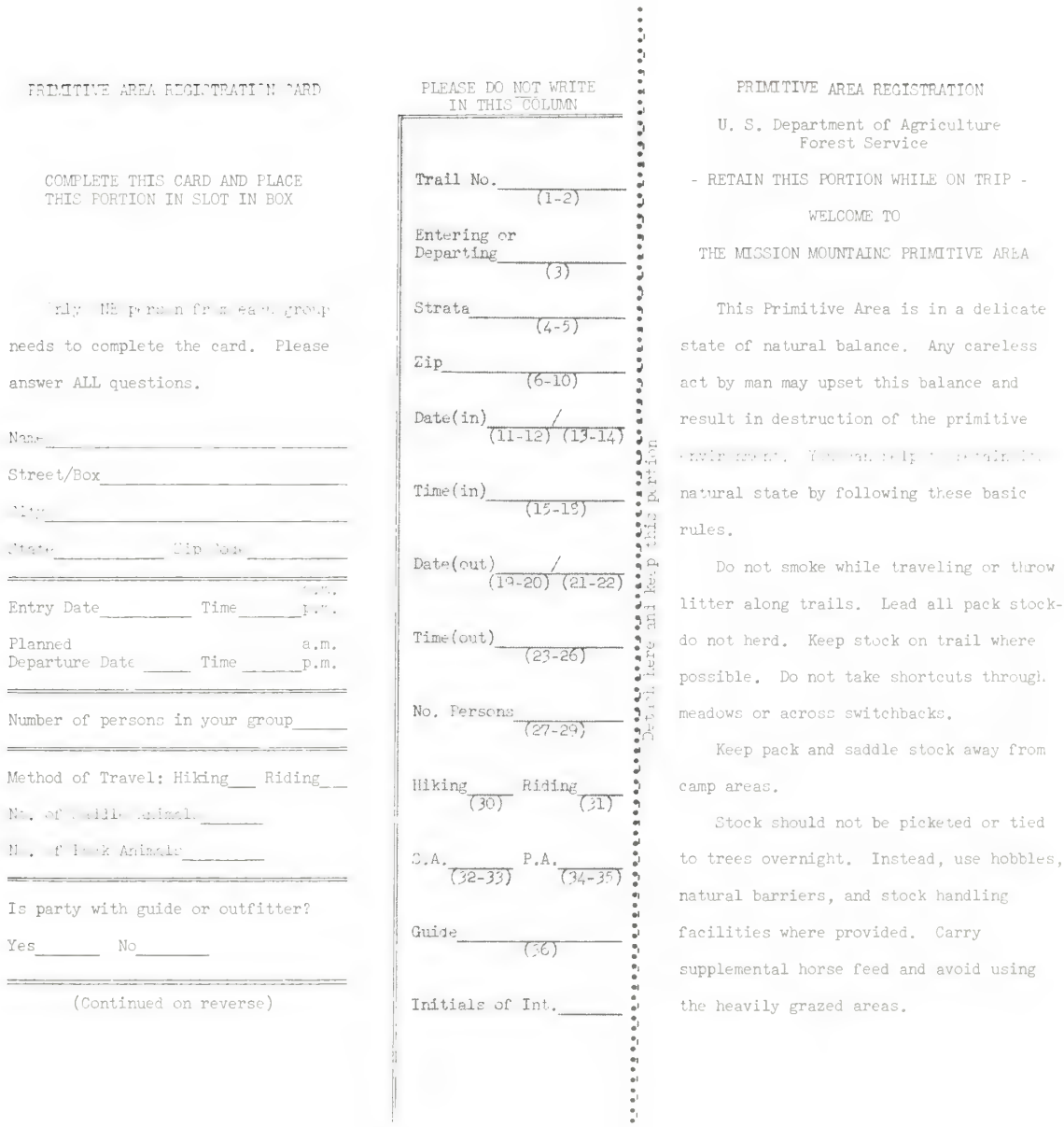
APPENDIX I

Primitive Area Registration Card



PRIMITIVE AREA REGISTRATION CARD

COMPLETE THIS CARD AND PLACE THIS PORTION IN SLOT IN BOX

Only ONE person from each group needs to complete the card. Please answer ALL questions.

Name_____

Street/Box_____

City_____

State_____ Zip Code_____

Entry Date_____ Time_____p.m.

Planned a.m.
Departure Date _____ Time _____p.m.

Number of persons in your group_____

Method of Travel: Hiking___ Riding___

No. of Saddle Animals_____

No. of Pack Animals_____

Is party with guide or outfitter?

Yes_____ No_____

(Continued on reverse)

PLEASE DO NOT WRITE IN THIS COLUMN

Trail No._____ (1-2)

Entering or Departing_____ (3)

Strata_____ (4-5)

Zip_____ (6-10)

Date(in)_____/_____ (11-12) (13-14)

Time(in)_____ (15-18)

Date(out)_____/_____ (19-20) (21-22)

Time(out)_____ (23-26)

No. Persons_____ (27-29)

Hiking_____ (30) Riding_____ (31)

S.A._____ (32-33) P.A._____ (34-35)

Guide_____ (36)

Initials of Int._____

Detach here and keep this portion

PRIMITIVE AREA REGISTRATION

U. S. Department of Agriculture
Forest Service

- RETAIN THIS PORTION WHILE ON TRIP -

WELCOME TO

THE MISSION MOUNTAINS PRIMITIVE AREA

This Primitive Area is in a delicate state of natural balance. Any careless act by man may upset this balance and result in destruction of the primitive environment. You can help maintain its natural state by following these basic rules.

Do not smoke while traveling or throw litter along trails. Lead all pack stock-do not herd. Keep stock on trail where possible. Do not take shortcuts through meadows or across switchbacks.

Keep pack and saddle stock away from camp areas.

Stock should not be picketed or tied to trees overnight. Instead, use hobbles, natural barriers, and stock handling facilities where provided. Carry supplemental horse feed and avoid using the heavily grazed areas.

Figure 9. — Front side of the registration card used for the study.

[illegible] map which [illegible] your trip. ENTER HERE the number or numbers of the compartments that you plan to [illegible]. _____ _____

If you are planning to stay overnight, name the places you plan to camp and the number of nights planned for each place.

Place	No. Nights	Place	No. Nights

Which of the following activities do you (and your group) plan to engage in during your visit? State in each one how many of you plan to do the particular activity. Complete as many as needed.

Fishing	☐	Riding	☐
Hiking	☐	Camping	☐
Mountain Climbing	☐	Other (specify)	☐
Hunting	☐		
[illegible]	☐		

F.S.F. No. 40-S68048 12/31/68
USDA-Forest Service

[illegible] WRITE IN BOX [illegible]

Compartments _____ (37-38)

_____ (39-40) _____ (41-42) _____ (43-44)

Destinations/Nights

_____ / _____ (45-46) (47) _____ / _____ (48-49) (50)

_____ / _____ (51-52) (53)

Activities, Participants

F._____ (54-55) R._____ (64-65)

H._____ (56-57) C._____ (66-67)

H._____ (58-59) O._____ (68-69)

M.C._____ (60-61) _____ (70)

N.S._____ (62-63) _____ (71)

Region _____ (72)

State _____ (73-74)

Wilderness _____ (75-76)

Forest _____ (77-78)

Dist._____ (79-80)

Detach this part and keep [illegible]

Use existing campsites and fireplaces. Do not cut green trees or boughs--use only dead material for tent poles, pegs, and firewood. Remove all temporary camp facilities before leaving.

Burn all refuse and pack out all cans, bottles, and foil. Be sure your fire is dead out. Take pride in leaving the site in better condition than you found it.

Each pack string must carry an ax with 26" handle and 2-pound head, a shovel with 30" handle and 6" wide blade, and a one-gallon water container.

THANK YOU FOR YOUR COOPERATION

The information you provided helps the Forest Ranger to know your needs and to better maintain this area as a potential Wilderness.

WOOD · WATER · FORAGE · WILDLIFE · RECREATION

Figure 10. – Back side of the registration card used for the study.

APPENDIX II

Formula Used to Calculate Standard Errors for Estimated Registration Rates

The formula (Cochran, 1963, section 6.11) used to derive standard error follows:

$$\text{var } Y_h = R^2_h \frac{\left(1-\frac{r_h}{R_h}\right)}{r_h}\left[S^2_{m_h} + Y_h{}^2 S^2_{n_h} - 2Y\rho_h S_{m_h} S_{n_h}\right]/M_h$$

for individual strata, and for pooled estimates

$$\text{var}(Y) = \sum_{h=1}^{7} R^2_h \frac{\left(1-\frac{r_h}{R_h}\right)}{r_h}\left[S^2_{m_h} + Y_h{}^2 S^2_{n_h} - 2Y\rho_h S_{m_h} S_{n_h}\right]/M_h .$$

To estimate weighted means for pooled strata, we used

$$Y = \frac{\sum_{h=1}^{7} \frac{R_h}{R} \sum_{i=1}^{r_h} \frac{m_{hi}}{r_h}}{\sum_{h=1}^{7} \frac{R_h}{R} \sum_{i=1}^{r_h} \frac{n_{hi}}{r_h}}$$

where

Y_h = estimated registration rate in stratum h; Y = overall estimated rate;

R_h = actual total number of sample units in stratum h;

$R = \sum_{h=1}^{7} R_h$, or the total number of sample units;

r_h = the number of selected sample units in stratum h;

M_h = the number of registered groups;

m_{hi} = the number of registered sample groups from sample unit i, stratum h;

n_{hi} = the total number of sample groups from sample unit i, stratum h;

$S^2_{m_h}$ = variance of m_h (and similarly for n_h);

ρ_h = estimated correlation of m_{hi} and n_{hi}.

APPENDIX III

Variables and Notation Used in Study

Variables and notation used in this study include:

X_i: registration information for variable i.

Y_i: interview information (entering) for variable i.

Z_i: interview information (leaving) for variable i.

Variables of interest include:

Number of visits (i = 1)
Number of hiking groups (i = 2)
Number of riding groups (i = 3)
Number of saddle horses (i = 4)
Number of pack horses (i = 5)
Recreation use in visitor-hours (i = 6)
Number of groups (i = 7)
Number of groups with guide (i = 8)
Number of one-person groups (i = 9)
Number of two-person groups (i = 10)
Number of groups with local ZIP code 598XX (i = 11)
Number of groups with local ZIP code 599XX (i = 12)
Number of groups with local ZIP codes 594XX, 596XX, or 597XX (i = 13)

Table 10.--*Totals from registration cards for 13 study variables, by stratum.*

Variable	Stratum									
	1	2	3	4	5	6	7	Summer	Fall	Total
Number of:										
Visits (X_1)	658	597	570	880	140	136	78	2,705	354	3,059
Hiking groups (X_2)	163	167	133	168	48	42	19	631	109	740
Riding groups (X_3)	3	2	4	40	3	11	7	49	21	70
Saddle animals (X_4)	6	0	16	172	6	34	11	194	51	245
Pack animals (X_5)	0	0	0	65	1	7	1	65	9	74
Total use, hours (X_6)	6,511	4,533	3,932	15,289	1,397	2,375	755	30,265	4,527	34,855
Number of:										
Groups (X_7)	166	169	137	208	51	53	26	680	130	810
Groups with guides (X_8)	1	4	1	19	2	2	0	25	4	29
One-person groups (X_9)	7	20	7	19	3	6	4	53	13	66
Two-person groups (X_{10})	40	50	39	62	21	29	12	191	62	253
Groups with ZIP code 598XX (X_{11})	93	53	62	119	26	17	13	327	56	383
Groups with ZIP code 599XX (X_{12})	20	24	31	16	17	23	9	91	49	140
Groups with ZIP codes 594XX, 596XX, or 597XX (X_{13})	19	22	6	16	3	6	1	63	10	73

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